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Influence of Willow Root Density on Shear Resistance Parameters in Fine Grain Soils using *in situ* Direct Shear Tests

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ABSTRACT

This study presents an experimental study on the effect of root density on the shear strength of fine grain soils by conducting *in situ* direct shear tests. The plant used in the shear tests was Willow, a tree compatible with the climates of many sliding regions in Iran. Stabilization of river terraces and natural soil slopes by means of tree roots as a reinforcement agent is an environmental adopted method which needs to be developed. In this research a series of tests was carried out on soil blocks both containing and without Willow roots using a large scale *in situ* direct shear test apparatus. The results were analyzed based on direct shear theory to calculate the apparent cohesion and internal friction angle of rooted and non-rooted soil. The results reveal that in spite of a slight decrease of 5% in the internal friction angle, the apparent cohesion of lean clay soils increases significantly up to 80%. Since, the effect of tree roots on the improvement of shear strength in lower depths is less than surface layers, implanting Willow is recommended as an effective technique for preventing superficial sliding. The results of this research are presented in forms of linear relations between increased apparent cohesion and shear strength and Willow root density (RAR) at different depths of soil.

Key words: Willow, shear strength, cohesion, internal friction angle, root density

INTRODUCTION

The role of vegetation in the stability of slopes has gained increasing recognition from the viewpoint of mechanical and hydrological impacts (Greenway, 1987). So far, some simple force equilibrium models for evaluating the additional soil shear strength provided by roots have been developed by Wu (1976), Wu *et al.* (1979) and Gray and Lieser (1982). In addition, analytical models for soil-root interactions were developed by Waldron (1977), Waldron and Dakessian (1981) and Wu *et al.* (1988a) which were employed to analyze *in situ* direct shear test results (Wu *et al.*, 1988b; Wu and Watson, 1998). Furthermore, laboratory shear tests and *in situ* shear tests on root-reinforced soil blocks were conducted by several researchers such as Endo and Tsuruta (1969), Wu *et al.* (1988b), Tobias (1995), Wu and Watson (1998) and Operstein and Frydman (2000).

According to these researches, small size flexible roots mobilize their tensile strength to increase the soil-fiber compound strength (Gray and Leiser, 1982), whereas large size roots act as individual anchors (Coppin and Richards, 1990) and eventually tend to slip through the soil matrix and mobilize a small portion of their tensile strength (Burroughs and Thomas, 1977; O'Loughlin and Watson, 1979; Schmidt *et al.*, 2001; Ziemer, 1981).

Waldron (1977) and Wu (1976) reported that the extent of the influence of root reinforcement on the shear resistance of soil depends on the density, tensile strength and depth of roots, which vary significantly as a function of species, local environmental characteristics and spatial variability of vegetation properties such as density, age, fire events, erosion, trees health, etc.

Hengchaovanich and Nilaweera (1996), Waldron and Dakessian (1981) and Waldron (1977) examined the relationship between increased shear strength and root density in a loam-clay and a loam-silty-clay soil and found a linear relation between them. Bajestan and Golshaikhi (2003) reported the following linear relationship to calculate shear strength added to a loam-silty soil due to presence of Tamarisk and Sinde Poplar roots in which RAR represents the root density and value of α for the two plants is 7.3 and 4.2, respectively:

$$\Delta S = \alpha.RAR \qquad (1)$$

Many researchers such as Wu *et al.* (1979), Luckman *et al.* (1982), Coppin and Richards (1990), Abe and Ziemer (1991) and Yarbrough (2000) studied theoretically the mechanism of root effect on soil strength and the transformation of root tensile strength to apparent cohesion and friction between soil particles. Some researchers believe that the effect of plant root on internal friction angle (φ) is negligible (e.g., Endo and Tsuruta, 1969; O'Loughlin, 1974a, b; Swanston, 1974a, b; Waldron, 1977; Gray and Megahan, 1981; Waldron and Dakessian, 1981), but some others believe different. For example, Tengbeh (1989) reported plant roots do not affect the internal friction angle in loam-sandy-clay soil but they do increase φ in sandy soil. Also Davoudi *et al.* (2006a) reported Willow root can decrease φ to 10% depending on the root diameter. Other researchers such as Abe and Ziemer (1991) and Stokes *et al.* (1995, 1996) have reported different results based on laboratory tests.

In situ tests for evaluating the influence of tree roots on the soil shear resistance is classified in two groups: pull out test and direct shear test. Some researchers such as Nilaweera (1994), Nilaweera and Nutalaya (1999) and Stokes *et al.* (1996) have used the first method, but due to theoretical easiness in results analysis, more interest has been paid to the second method; e.g., Wu and Watson (1998), Greenway (1987), Abe and Iwamoto (1986) and Ekanayake and Phillips (2002). In this test, according to the theory of direct shear test, after isolating a soil block from its surrounding, a certain vertical stress is applied to it, then its shear strength against failure is measured by applying a horizontal shear force to it. Up to now, all foresaid researchers except the last one, have carried out their tests without vertical stress. Therefore, their results are not applicable in practical projects and moreover, the soil shear strength parameters, i.e., the apparent cohesion and the internal friction angle, are not calculable. In this research, series of field experiments have been carried out using *in situ* direct shear test apparatus, while the deficiency explained above has been overcome.

MATERIALS AND METHODS

Root density in soil has been defined by Burroughs and Thomas (1977) as the roots cross sectional area per unit soil surface and is calculated through the following relation:

$$RAR = \frac{A_r}{A_t}100 = \frac{\sum a_i}{A_t}100 = \frac{\pi}{4}\frac{\sum d_i^2}{A_t}100 \qquad (2)$$

where, A_t is the cross section of soil block along failure plane, A_r is the surface occupied by roots in the same section, a_i and d_i are cross section and diameter of roots, respectively.

The live root of Willow tree was used because this tree is compatible with the climate of many sliding regions in Iran. Figure 1 shows location of study site (Minavanad village) in Taleghan region, Iran. The experiments were carried out using an *in situ* direct shear test apparatus designed and built in The Research Institute for Water Scarcity and Drought (Davoudi *et al*., 2006a). The apparatus is consisted of the following parts: shear box for holding soil blocks, hydraulic jacks for applying shear and vertical forces, gauges for measuring horizontal and vertical deformations of soil, gauges for detecting horizontal and vertical pressure, support plates, axial load plate and loading plateform consisted of framework, surcharge and roller support (Fig. 2). A test pit with dimensions of 150*150 cm^2 was dug and after reaching the desired depth, a soil block with horizontal dimensions of 50*50 cm^2 and 30 cm height was left untouched at the bottom of the pit. A bottomless and topless shear box with dimensions identical to the block was slightly fitted to the block from the top to maintain it rigid during the test. After installing two horizontal and four vertical displacement gauges, a vertical jack was placed over the soil block to transfer the weight of the surcharge to provide the vertical stress to the soil block. For the consolidation process to be completed, a certain time was given to the soil. Then horizontal shear force was applied to the shear box step by step and the values of shear stress and horizontal displacements were recorded every 30 sec with 0.01 mm resolution. The vertical stress was also recorded every 2 min. The experiment continued with a rate of 0.2 mm horizontal displacement per minute until a continuous decrease in shear strength was observed or 50 mm horizontal displacement was reached. At the end, the number and diameter of the roots in the shear region of the block were measured. For every test, one block was prepared and used. The blocks were far from each other at least one meter in vertical distance or three meters in horizontal distance. All experiments were carried out under a vertical stress of 20, 59 or 98 kPa. Fourteen tests were carried out in Minavand village where its soil is lean clay (CL), composed of 32% gravel, 16% sand, 18% silt and 34% clay. Six experiments were performed in soil without root and the others in soil containing Willow root (Table 1).

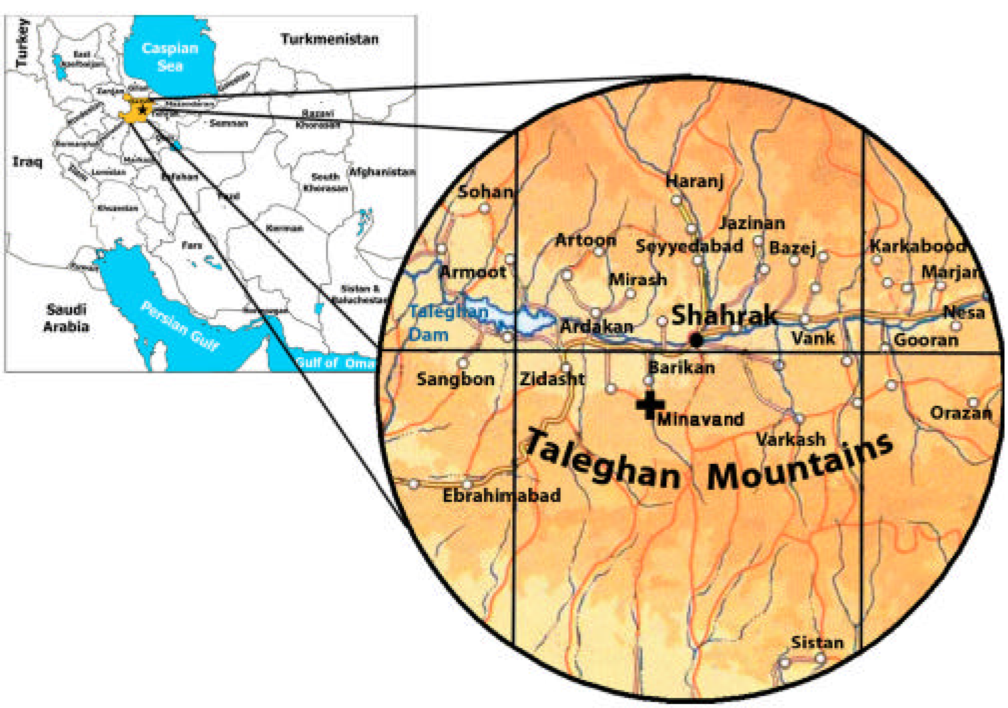

Fig. 1: Location map of the study site, Minavand village

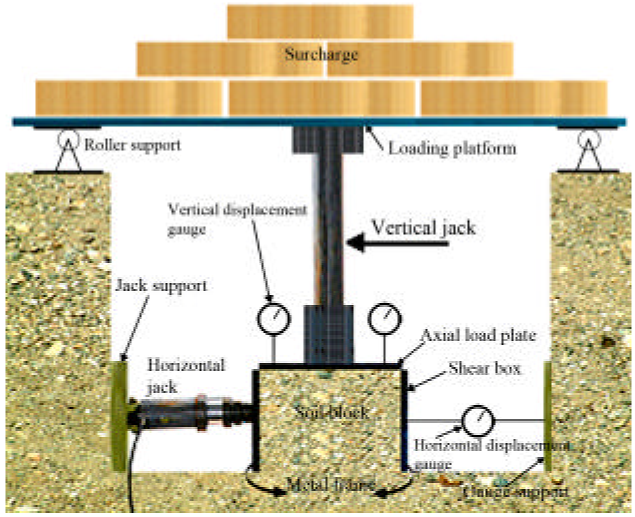

Fig. 2: A schematic illustration of *in situ* direct shear test apparatus

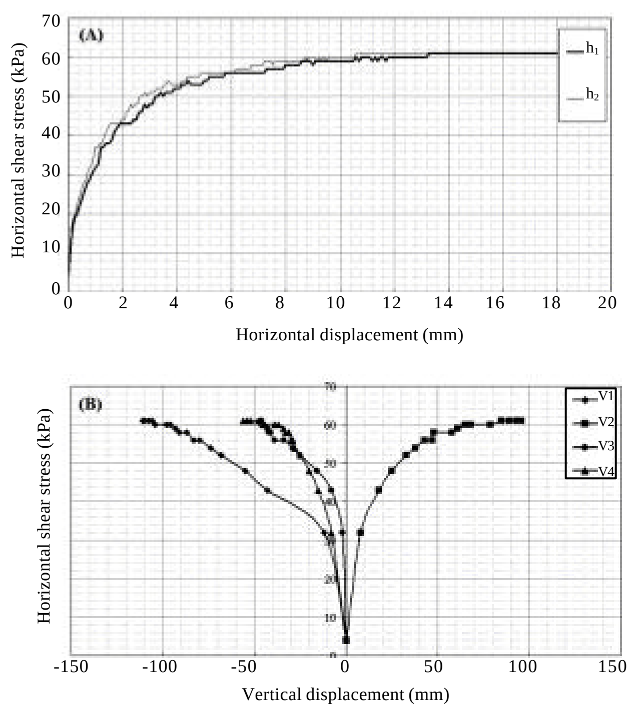

Fig. 3: Soil block displacement against shear stress under vertical stress of 98 kPa in soil without root: (A) horizontal displacement using two gauges (h_1 and h_2) and (B) vertical displacement using four gauges

Figure 3 and 4 present detailed results of the two tests carried out in Minavand as example. Horizontal displacement against shear stress under a vertical stress of 98 kPa for a block without root and a block having a root density of 0.51% are illustrated in Fig. 3A and 4A, respectively. Figure 3B and 4B represent vertical displacement against shear stress of foresaid blocks.

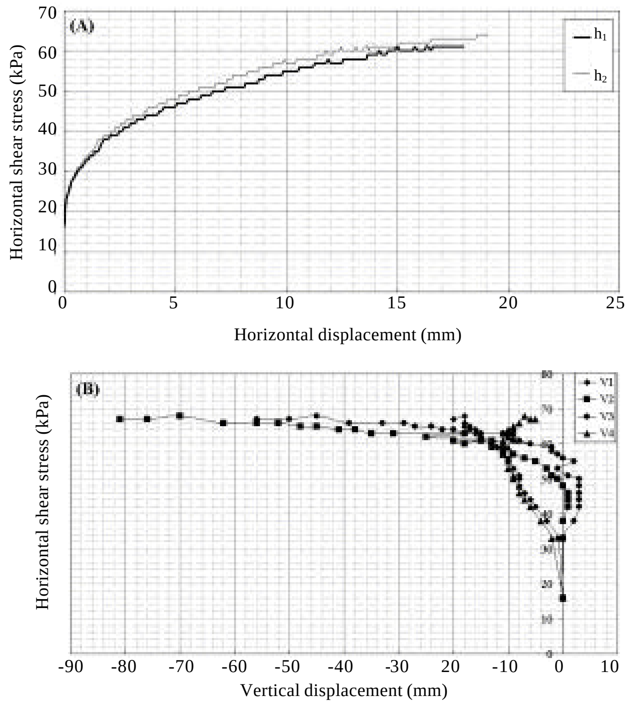

Fig. 4: Soil block displacement against shear stress under vertical stress of 98 kPa in soil with root density (RAR) of 0.51% and 50 cm depth: (A) horizontal displacement using two gauges (h_1 and h_2) and (B) vertical displacement using four gauges

Table 1: Sight soil properties

Soil class	Soil type	Dry density (ρ_d)	Natural moisture content (ω)	Liquid limit (LL)	Plasticity index (IP)
			(%)		
CL	Gravelly lean clay	1.75	17	30	12

RESULTS AND DISCUSSION

The results of all tests are presented in Table 2 where, d_{50} and d_{max} are mean and maximum diameter of roots in a block, respectively and τ_{max} is the maximum shear stress of soil block under vertical stress of σ_υ.

As the experiments were carried out in natural and uncontrollable situations, it is impossible to find soil blocks with identical root density. Therefore the blocks were classified based on their Root Area Ratios (RAR) then the internal friction angle (φ) and the apparent cohesion (c) of each group were determined (Table 3). In all groups, the maximum shear strength of three experiments under three different vertical stresses were illustrated in a Cartesian coordinate system to find the failure envelope and then the values of internal friction angle and cohesion. As an example, the failure envelope for a range of root density RAR = 4.05-5.64% is illustrated in Fig. 5.

A distinct difference is observed between apparent cohesion of the soil blocks with and without root such that the value of apparent cohesion increases from 7.5 to 13.5 kPa. Figure 6 shows the variation of apparent cohesion with respect to RAR.

It should be noted that the rate of increase in soil properties, in addition to RAR, is a function of root diameter, soil density and its plasticity index as cited by Davoudi *et al.* (2006b). He explained

Table 2: The results obtained by *in situ* direct shear tests on soil blocks with and without willow root

			d_{50}	d_{max}	σ_v	τ_{max}
Test pit	RAR (%)	No. of roots	(mm)		(kPa)	
M1	0	0	-	-	20	26.9
	0	0	-	-	59	63.9
	0	0	-	-	98	103.5
M2	0	0	-	-	20	27.4
	0	0	-	-	59	65.5
	0	0	-	-	98	105.6
M3	9.57	256	3.1	62	20	29.9
M4	25.70	303	7	61	20	37.2
	12.04	319	5.1	32	59	76.3
	12.94	344	5	45	98	106.3
M5	26.15	212	4.9	68	59	88.9
	5.64	129	8.5	36	98	99.6
M6	4.05	175	4	35	20	27.7
M7	5.00	186	6	23	59	66.8
	11.22	94	4.6	105	98	99.5

Table 3: Soil shear strength parameters for different root density classes

					ΔC		Δφ	
RAR class (%)	RAR average	d_{50} (mm)	c (kPa)	φ (°)	(kPa)	(%)	(°)	(%)
0	0	0	7.5	44.9	0	0	0	0
4-6	4.89	4.4	10.8	42.5	3.3	44	-2.4	-5
9-13	11.52	6.2	13.5	44.3	6	80	-0.6	-1

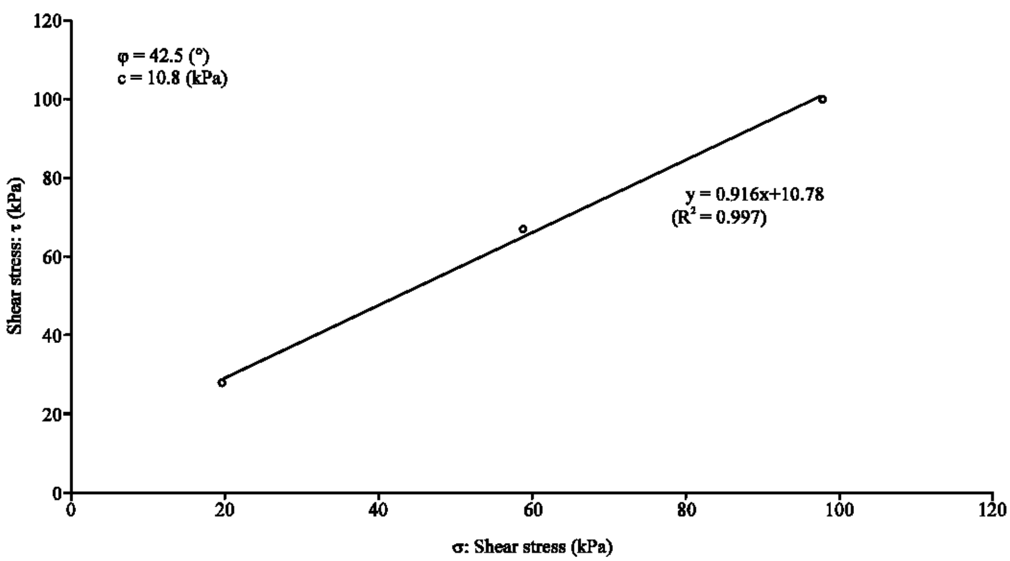

Fig. 5: Failure envelope and determining shear strength parameters for three soil blocks with root densities between 4.05-5.64%

that the smaller the root diameter, the lower the soil density and the higher the plasticity index, the higher is the efficiency of root reinforcement. However, under present circumstances the rate

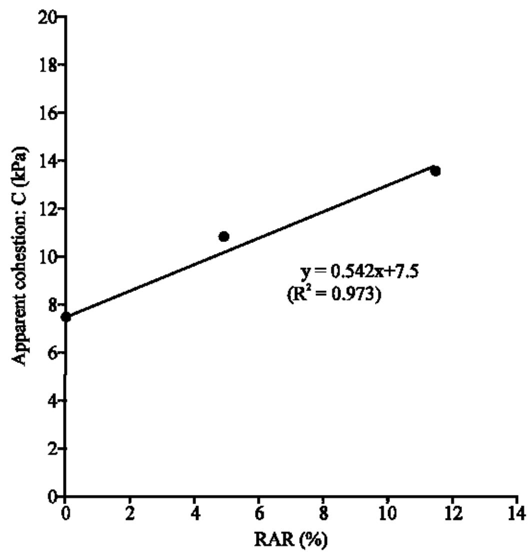

Fig. 6: Variation of apparent cohesion of rooted soil mass against root area ratio

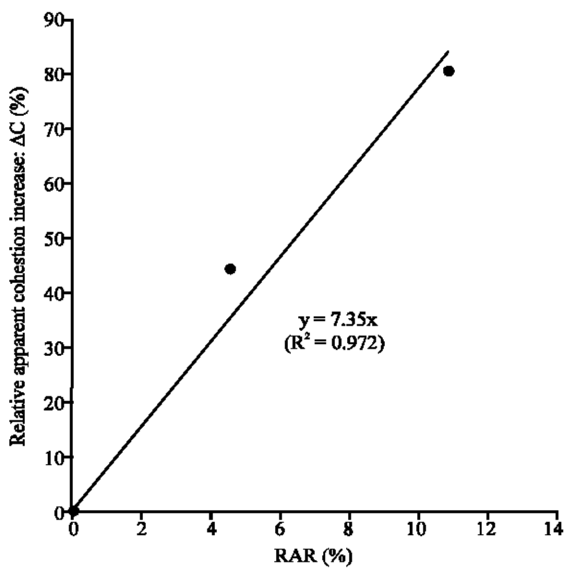

Fig. 7: Variation of relative increase in apparent cohesion of rooted soil versus root area ratio

of variation of the apparent cohesion due to Willow root for the used soil is as follows, whereas c is in kPa:

$$c = 7.5+0.54\ \text{RAR} \tag{3}$$

The variation of relative increase of apparent cohesion of the soil block (Δc) due to Willow root is illustrated in Fig. 7. As shown, with increasing root density (RAR), the relative increase of apparent cohesion rises distinctly up to 80% by the following rate:

$$\Delta c = 7.35\ \text{RAR} \tag{4}$$

where as, Δc is defined by the following relation in which c and c_0 are the cohesion of root-reinforced and free-root soil, respectively:

$$\Delta c = \frac{c - c_0}{c_0} \times 100 \tag{5}$$

As indicated in Table 3, the effect of root on internal friction angle of soil, contrary to cohesion, is negative. This is in accordance with Davoudi (2006) reporting that root reinforcement causes to decrease the internal friction angle depending on the root diameter. In these tests, it decreased between 0.6 and 2.4 degrees which is equivalent to 1-5% of internal friction angle of free-root soil. However, the decrease of φ is so little that one may consider it as order as tests accuracy and thus ignore the effect of root on the internal friction angle. This is confirmed by Fig. 8 in which horizontal deformations of three blocks under three normal stresses of 98, 59 and 20 kPa are illustrated while the magnitude of RAR in them are 11.2, 5 and zero, respectively. As revealed, all blocks demonstrated identical non-brittle behaviors and since the difference between their normal stresses is almost equal, they experienced almost equal differences between their maximum shear resistances.

In order to deliberate the direct effect of Willow roots density on the shear strength of soil; the results were plotted versus RAR under normal stresses. Figure 9 presents variation of shear strength of rooted soil under three normal stresses of 20, 59 and 98 kPa, which are equivalent to a soil depth of somewhat around 1.1, 3.4 and 5.6 m. Soil blocks under normal stress of 98 kPa reveal almost unchanged such that a very low improvement is observed in the shear strength with respect to RAR, while other series demonstrate a fair sensibility to root reinforcement and their shear strength improve significantly with RAR.

The following linear equations represent the relation between mobilized shear strength in the gravelly lean clay of the site containing willow root under 20, 59 and 98 kPa overburden pressure, respectively:

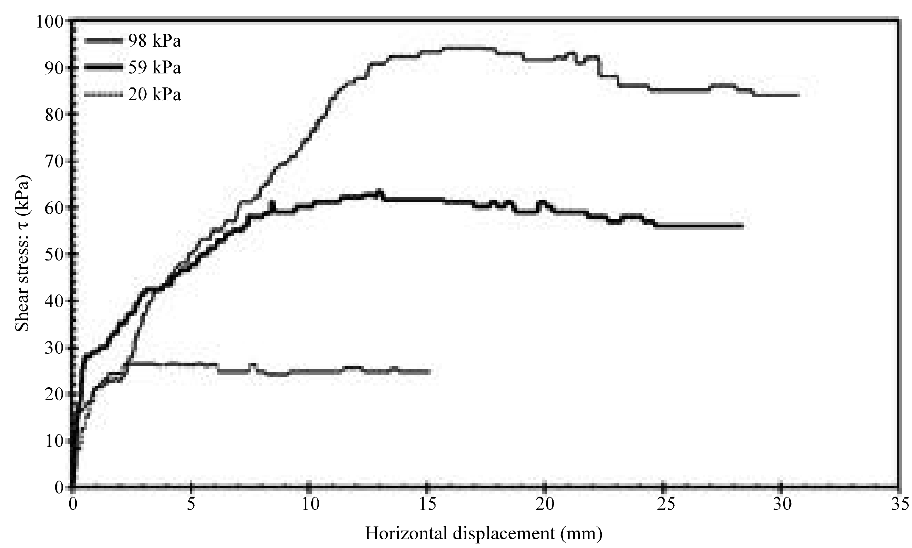

Fig. 8: Behaviors of three blocks containing root densities of 11.2, 5 and zero under different vertical stress demonstrating the dominance of apparent cohesion on the mobilized shear resistance

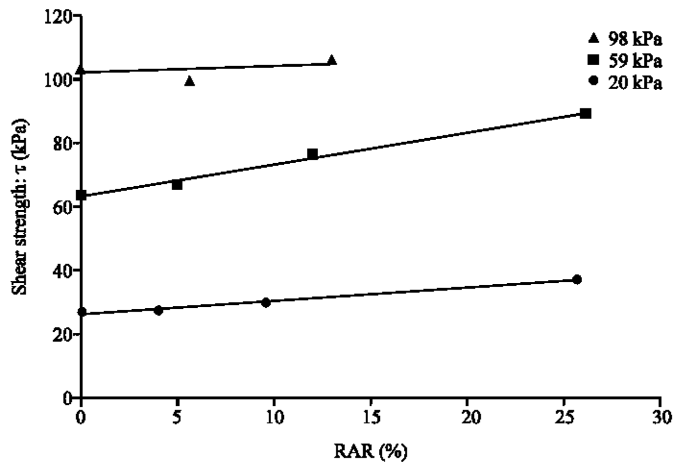

Fig. 9: Variation of shear strength of rooted soil against root area ratio under vertical stress of 20, 59 and 98 kPa

$$\tau = 26.4+0.41\ \text{RAR} \tag{6}$$

$$\tau = 63.3+0.99\ \text{RAR} \tag{7}$$

$$\tau = 101.5+0.25\ \text{RAR} \tag{8}$$

As revealed the increase in shear resistance of soil is significantly relevant to the overburden pressure. The relative increase of shear strength due to root density is defined by the following equation where τ and τ_0 are the shear strength of rooted and non rooted soil, respectively:

$$\Delta\tau = \frac{\tau - \tau_0}{\tau_0} \times 100 \tag{9}$$

Figure 10 presents the variation of relative increase of shear strength of the gravelly lean clay soil of Minavand with respect to Willow root density under different vertical stresses. The blocks under 98 kPa remain unchanged; but under 20 and 59 kPa the shear strength of soil improves sharply and for a root density of 26% rises somewhat about 40%.

One may use the following equation for prediction of Maximum relative increase in the shear strength which is in good accordance with the results of Davoudi *et al.* (2006b) reporting that the maximum achievable increase in safety factor of a natural slope via willow root reinforcement is 36%. However, it should be noted that this property is a function of overburden pressure such that it increases as the soil depth increases until a certain depth after which starts reducing gradually with soil depth and for deep soils it approaches to zero.

$$\Delta\tau_{max} = 1.4\ \text{RAR} \tag{10}$$

It is important to note that scattering in data of Fig. 10 is usually caused by the difference between root diameters. In addition, the difference between natural humidity of the soil blocks is another uncontrollable parameter influencing the results.

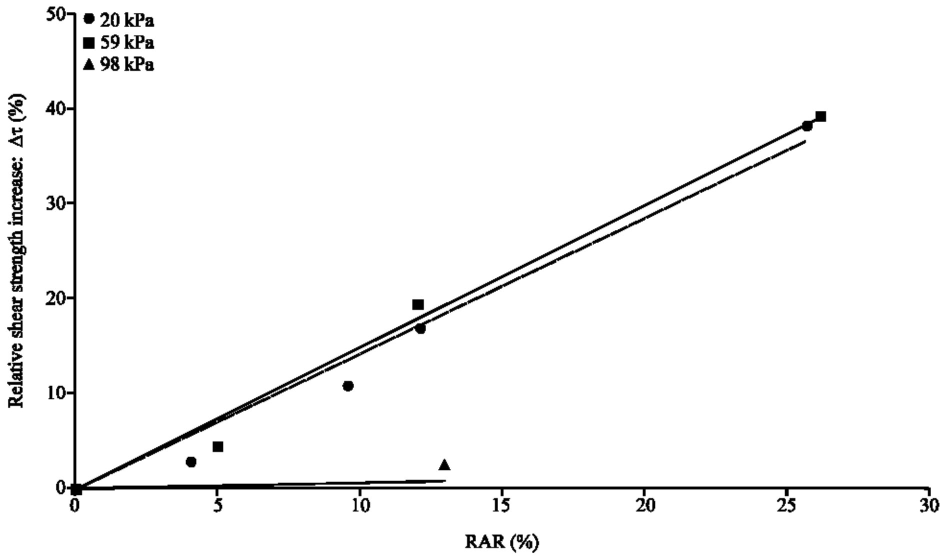

Fig. 10: Variation of relative increase of shear strength of rooted soil versus root area ratio under vertical stress of 20, 59 and 98 kPa

To compare with previous researches the experimental results obtained in this research were used to establish a relationship between the increase in shear resistance of soil and the tensile strength of all roots located in the shear zone assuming that the tensile stress of all roots is fully mobilized during failure process of blocks. The mobilized tensile strength in unit area of shear plane (T_R) is calculated by the following relation in which T_i is tensile strength of individual roots:

$$T_R = \Sigma \frac{T_i a_i}{A_t} \tag{11}$$

Using relation between willow root diameter and its tensile strength from Davoudi (2006), the value of T_R for blocks under 20 and 59 kPa normal stresses were calculated and illustrated versus the increase in shear resistance (τ-τ_0) in Fig. 11 in from of dashed line. Two linear relations with a high correlation factor were driven in form of Eq. 12 in which the coefficient β has a magnitude of 0.64 and 1.59 for blocks subjected to a normal stress of 20 and 50 kPa equivalents to 1.1 and 3.4 m overburden pressure, respectively.

$$(\tau\text{-}\tau_0) = \beta T_R \tag{12}$$

This relation is similar to those presented by some researchers but the magnitude of coefficient is quite different. Fan and Su (2008) by conducting *in situ* shear tests on silty sand soil samples without applying normal stress reported $\beta = 0.39$. They also expressed that in the relation presented by Wu *et al.* (1979) for calculating shear resistance improvement:

$$(\tau - \tau_0) = T_R(\cos\theta.\ \tan\phi' + \sin\theta) \tag{13}$$

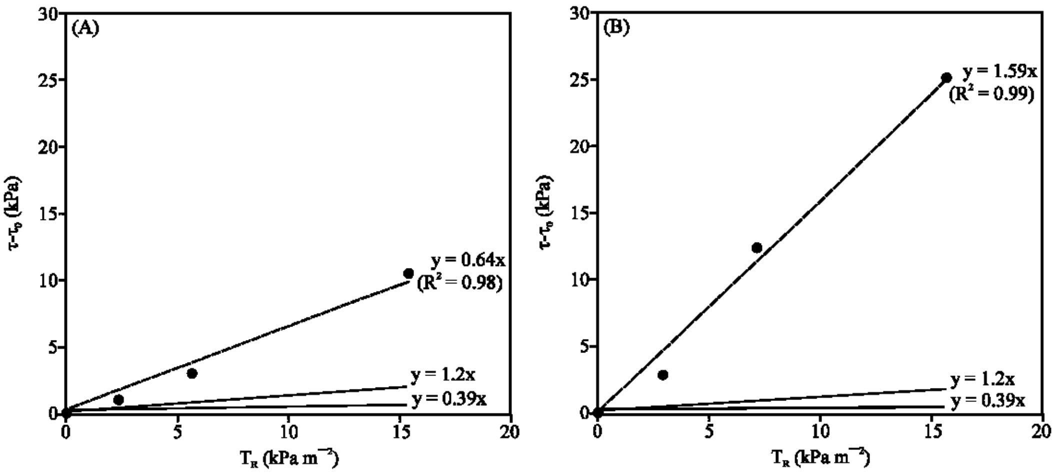

Fig. 11: Relation between the increase in shear resistance and the mobilized tensile strength in unit area of shear plane in samples under normal pressure: (A) 20 kPa and (B) 59 kPa

The right side parenthesis is an insensitive function of angle of shear distortion of root (θ) and is close to 1.2 for large range of it, so they theoretically concluded $\beta = 1.2$ while Ruebens *et al.* (2007) proposed a general value of $\beta = 1.15$.

Comparison between values of β obtained in this research which has bees been done on a lean clay soil and that proposed by Fan and Su (2008) which has been carried out on a silty sand soil shows that:

- Regardless the type of root and its diameter, the type of soil is very important in the value of β. The engagement between soil and root is determining in the transfer of the tensile strength mobilized in the root to the soil mass. Since, this engagement is much higher in fine grain soils than in coarse grain ones, a higher portion of root strength is transferred to the soil matrix. In other words, in a cohesive and fine grain soils containing plant root, due to a desired engagement between components, the media behaves as a continuous and unit system and presents a higher resistance against driving force. While in non-cohesive and coarse grain soils the two components act more and less independently and thus less strength is transferred from roots to soil matrix. In general one may conclude that in fine grain soils, with increasing the cohesion, the plasticity and the water content the value of β will increase too
- The overburden pressure also plays an important role in the magnitude of β. In the tests of Fan and Su (2008) didn't apply any vertical load in their tests and thus the normal stress on the shear plane was equal to the weight of soil blocks of a thickness of 10 cm and thus say a normal stress of 1.8 kPa and found a low value for $\beta = 0.39$, but in the tests carried out in this research the normal stress is much higher, 20 and 59 kPa and thus β is found relatively high as much as 0.64 and 1.59, respectively. This differences and particularly the difference between the two values obtained in the same soil and the same plant root reveal that, in addition to the soil and root specifications, the overburden pressure is very influencing. It is well known that confining pressure affect the friction between components and thus in a reinforced system containing soil and root, the overburden pressure is determinant for the extent of engagement between them. It's expected that the rate of influence of overburden pressure in the engagement of root and

soil matrix and thus the rate of strength transfer between them in fine grain soil is higher than that in coarse grain soil; however it needs to be studied more.

Regarding two above mentioned points, a parameter representing the engagement of root and soil matrix needs to be added in Eq. 13 and thus it should be modified to the following form in which K_e is the Coefficient of engagement of root and soil matrix.

$$(\tau - \tau_0) = K_e T_R (\cos\theta . \tan\phi' + \sin\theta) \tag{14}$$

Consequently in Eq. 12 parameter **β** is a function of soil and engagement parameters as shown below:

$$\beta = f(K_s, K_e, \theta) \tag{15}$$

in which, K_s is a factor representing soil specification (i.e., grain size distribution, plasticity, density and moisture).

CONCLUSIONS

The results of *in situ* direct shear tests on the soil with and without Willow root in Taleghan region of Iran show that the presence of live root renders little decrease in internal friction angle of the soil by about 5%. However, as the increase in cohesion is much more than the decrease in internal friction angle, the presence of root renders a significant increase in the shear strength of soil. The effect of cohesion on shear strength in lower depths is less than surface layers, therefore relative increase of shear strength in the vicinity of surface is much more than deeper zones and thus; implanting Willow is an effective technique for preventing superficial slipping.

The shear strength of fine grain soils containing live roots of Willow tree increases linearly as the root density increases. The rate of increased strength in this research was more than those reported by other researchers.

The apparent cohesion increases linearly with root density (RAR) and within the range of performed tests, it rises to 80%.

For practical purposes one may conclude that Willow tree with a relatively fair root density can increase the shear strength of fine grain soils somewhat about 20%.

The overburden pressure and soil characteristics play an important role in the engagement of root and soil matrix and thus the increased shear resistance of a root-reinforced soil.

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REFERENCES

Abe, K. and M. Iwamoto, 1986. Preliminary experiment on shear in soil layers with a large direct shear apparatus. J. Jap. For. Soc., 68: 61-65.

Abe, K. and R.R. Ziemer, 1991. Effect of tree roots on a shear zone: Modeling reinforced shear stress. Can. J. For. Res., 21: 1012-1019.

Bajestan, M.S. and M.S. Golshaikhi, 2003. Investigation of the effects of tree roots on shear strength of the Karoon Banks. J. Sci. Technol. Agric. Nat. Resour., 6: 27-40.

Burroughs, E.J.J.R. and B.R. Thomas, 1977. Declining root strength in douglas-fir after felling as a factor in slope stability. USDA Forest Service Research Paper, INT-190.

Coppin, N.J. and I.G. Richards, 1990. Use of Vegetation in Civil Engineering. 1st Edn., Construction Industry Research and Information Association, Butterworths, London, pp: 292-292.

Davoudi, M.H., 2006. Effect of root diameter on cohesion and internal friction angle of soil. J. Agric. Eng. Res., 7: 53-68 (In Perisan).

Davoudi, M.H., D. Nikkami and S.R. Emam Jomeh, 2006a. Large scale tests on the effects of tree roots on soil shear strength. Final Report of Research Project, Soil Conservation and Watershed Management Research Institute, Iran, pp: 157 (In Perisan).

Davoudi, M.H., S.M. Fatemi-Aghda and G. Shah-Alipour, 2006b. Effect of willow tree root on slope stability. Sci. Q. J. Geosci., 15: 84-93 (In Persian).

Ekanayake, J.C. and C.J. Phillips, 2002. Slope stability thresholds for vegetated hillslopes: A composite model. Can. Geotech. J., 39: 849-862.

Endo, T. and T. Tsuruta, 1969. The effect of tree's roots on the shear strength of soil. Annual Report of Hokkaido Branch Forest Experiment Station, Sapporo, Japan, pp: 167-182.

Fan, C.C. and C.F. Su, 2008. Role of roots in the shear strength of root-reinforced soils with high moisture content. Ecol. Eng., 33: 157-166.

Gray, D.H. and W.F. Megahan, 1981. Forest vegetation removal and slope stability in the Idaho batholith. USDA Forest Service, Research Paper, INT-271.

Gray, D.H. and A.J. Leiser, 1982. Biotechnical Slope Protection and Erosion Control. Van Nostrand Reinhold, New York, pp: 271.

Greenway, D.R., 1987. Vegetation and Slope Stability. In: Slope Stability anderson, M.G. and K.S. Richards (Eds.). John Wiley and Sons, Chichester, pp: 187-230.

Hengchaovanich, D. and N.S. Nilaweera, 1996. An assessment of strength properties of vetiver grass roots in relation to slope stabilization. Proceedings of the First International Conference on Vetiver, (FICV'96), Chiang Rai, Thailand, pp: 153-158.

Luckman, P.G., R.L. Hathaway and W.R.N. Edwards, 1982. Root systems, root strength and slope stability. Water and Soil Conservation Organization, Ministry of Works and Development, Internal Report No. 34, Wellington, New Zealand.

Nilaweera, N.S., 1994. Influence of hardwood roots on soil shear strength and slope stability in Southern Thailand. Ph.D. Thesis, Asian Institute of Technology, Bangkok.

Nilaweera, N.S. and P. Nutalaya, 1999. Role of tree roots in slope stabilization. Bull. Eng. Geol. Environ., 57: 337-342.

Operstein, V. and S. Frydman, 2000. The influence of vegetation on soil strength. Ground Improvement, 4: 81-89.

O'Loughlin, C.L. and A. Watson, 1979. Root-wood strength deterioration in Radiata pine after clearfelling. N. Z. J. For. Sci., 39: 284-293.

O'Loughlin, C.L., 1974a. The effect of timber removal on the stability of forest soils. J. Hydrol. (N.Z.), 13: 121-134.

O'Loughlin, C.L., 1974b. A study of tree root strength deterioration following clearfelling. Can. J. For. Res., 4: 107-113.

Ruebens, B., J. Poesen, F. Danjon, G. Guendens and B. Muys, 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. Trees-Structure Function, 21: 385-402.

Schmidt, K.M., J.J. Roering, J.D. Stock, W.E. Dietrich, D.R. Montgomery and T. Schaub, 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Can. Geotech. J., 38: 995-1024.

Stokes, A., A.H. Fitter and M.P. Coutts, 1995. Responses of young trees to wind and shading: Effects on root architecture. J. Exp. Bot., 46: 1139-1146.

Stokes, A., J. Ball, A.H. Fitter, P. Brain and M.P. Coutts, 1996. An experimental investigation of the resistance of model root systems to uprooting. J. Ann. Bot., 78: 415-421.

Swanston, D.N., 1974a. The forest ecosystem of southeast Alaska: 5-soil mass movement. USDA, Forest Service, General Technical Report-PNW-17.

Swanston, D.N., 1974b. Slope stability problems associated with timber harvesting in mountainous regions of the Western United States. USDA, Forest Service, General Technical Report-PNW-21.

Tengbeh, G.T., 1989. The effect of grass cover on bank erosion. Ph.D. Thesis, Soil College, Cranfield Institute of Technology, UK.

Tobias, S., 1995. Shear strength of the soil root bond system. Proceedings of the International Conference on Vegetation and Slopes, Stabilisation, Protection and Ecology, University Museum, Oxford, Sept. 29-30, Thomas Telford, London, pp: 280-286.

Waldron, L.J., 1977. The shear resistance of root permeated homogeneous and stratified soil. Soil Sci. Soc. Am. J., 41: 843-849.

Waldron, L.J. and S. Dakessian, 1981. Effect of grass, legume and tree roots on soil shearing resistance. Soil Sci. Soc. Am. J., 46: 894-899.

Wu, T.H., 1976. Investigation of landslides on Prince of Wales Island. Geotechnical Engineering Report 5. Civil Engineering Department, Ohio State University, Columbus, Ohio, USA.

Wu, T.H., W.P. McKinnell and D.N. Swanston, 1979. Strength of tree roots and landslides on prince of Wales Island, Alaska. Can. Geotech. J., 114: 19-33.

Wu, T.H., R.M. McOmber, R.T. Erb and B.E. Beal, 1988a. Study of soil-root interactions. J. Geotech. Eng., 114: 1351-1375.

Wu, T.H., P.E. Beal and C. Lan, 1988b. In-situ shear test of soil-root interactions. J. Geotech. Eng., 114: 1376-1394.

Wu, H.T. and A. Watson, 1998. *In-situ* shear test of soil blocks with roots. Can. Geotech. J., 35: 579-590.

Yarbrough, L.D., 2000. Channel bank stability analysis and design considering effects of riparian vegetation and root reinforcement. M.Sc. Thesis, University of Mississippi, Oxford.

Ziemer, R.R., 1981. The role of vegetation in the stability of forested slopes. Proceedings of the 27th World Congress International Union of Forestry Research Organizations, Sept. 6-17, Kyoto, Japan, pp: 297-308.