American Journal of Environmental Sciences 5 (4): 475-486, 2009
ISSN 1553-345X

In situ Shear Tests of Soil Samples with Grass Roots in Alpine Environment

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Abstract: Problem statement: The presence of vegetation increases the soil burden stability along slopes and reduces soil erosion. Its contribution is due to mechanical (reinforcing soil shear resistance) and hydrologic controls on streambank and superficial landslides. This study presented the results carried out from experimental *in situ* test focused to study the increased shear resistance of soil blocks due to root-reinforcement. A shear apparatus was set up in order to realize the measure. **Approach:** In this research the researchers tested the capacity root reinforcement of *Festuca pratensis*, *Lolium perenne* and *Poa pratensis* (*Poaceae* families), *Medicago sativa*, *Trifolium pratensis* and *Lotus corniculatus* (*Fabaceae* families*)* grass species widespread in the Alpine environment. **Results:** *In situ* shear tests results revealed that grass roots fail progressively and their tendency were to slip, without failing. Shear-strengths calculated for root-reinforced soil with *Fabaceae*, yielded values between 19 and 166% higher than directly measured shear-strengths in soil with no roots. The shear displacement had an increase included between 493 and 1.900%. The shear time was always superior. The clod with roots, after the trials, were always packed together. **Conclusion:** These data were lower than those obtained with *Poaceae* tests (from 50-318%), but the two grass families were functional for a grass mix useful in technical seeding.

Key words: Shear strength, grass root, *in situ* test, soil reinforcement, soil-root interaction

INTRODUCTION

The use of vegetation for preventing and controlling erosion to stabilize soil has been practiced throughout the world[1].

This property has been showed through several literatures studies and research based on back-analysis where displacement has been accurately supervised, on *in situ* and in laboratory shear tests of soil blocks with roots, on in laboratory root tensile strength tests[2-9].

The magnitude of these effects depends on root system development, that itself is influenced by many factors such as the genetic properties of species and the site environmental characteristics (soil texture and structure, aeration, moisture, temperature, competition with other plants).

There are two main mechanical effects of roots: The small size flexible roots mobilize their tensile strength by soil-root friction increasing the compound matrix (soil-fiber) strength[1012], whereas the large size roots that intersect the shear plane act as individual anchors[11,13] and can tend to slip through the soil matrix without breaking, mobilizing only a small portion of their tensile strength[4,9,14-16]. In additional analytical models for soil-root interactions have also been developed[3,17].

Much has been investigated and written about root growth, phenology and function but very little attention has been given to the aspects of grass roots concerning stabilization of slopes. Their contribute is effective in the first 30 cm soil depth after few months from their seeding.

The contribution in shear resistance offered by *Poa pratensis* root has been studied by Tobias[18] in a test site on a hillslope in the Alps (Switzerland) using a shear box (500×500×150 mm deep); he measured that a slope stability increase respect the rootless soil varying between-2 and 55%. Lawrence *et al*.[19] tested soil with *Pennisetum purpureum*, *Cymbopogon microtheca*, *Themeda* sp., *Neyraudia* sp, *Setaria anceps* and *Imperata* sp.used a shear box (250×250×100 mm deep), a hand-powered jack, a dial gauge and a compression force transducer; the increase measured respect the rootless soil was included between -48 and 56%.

Wu and Watson[3] made trials in the Ashley Forest, in New Zealand, with various species of 6-8 years planted trees, dominated by *Pinus radiata*; they used hydraulic jacks, that acted on steel plates placed in a

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trench 0.5 m deep, a pressure transducer, a rotary potentiometer attached to the tree stump and vertical flexible plastic tubes (placed in the block and used as a simple slope indicator); the measured and calculated shearing resistances were about 21.6 kN.

Normaniza and Barakbah[8] made shear strength tests with a simple field inspection vane.

In view of this, the objective of this study is describe the shear apparatus designed and realized on purpose and present the obtained results. The apparatus was carried out to investigate the strengthening effects of plants on soil shear strength properties. A phenomenon of shallow landslides has been simulate.

This investigation provides values of root shear resistance of grass species that can been used to control soil erosion and to revegetated soil.

Shallow landslides: An hillslope can be perturbed by shallow and or superficial landslide. They can be stabilized either by reducing the failure forces or by increasing the resistance ones. Vegetation contributes to mass stability by increasing soil shear strength through root reinforcement[23].

In particular the shallow landslides are situations where the failure interests a soil depth of about 15-50 cm and they can be generated by a storm event in few hours, reaching very low speed (until 1-5 km mm^{-1}), low value in comparison with superficial landslide where the soil depth is about 80-100 cm and speed (until 50 km mm^{-1})[20,27].

The forces acting on hillslopes can be compared thinking the boundary balance of a prismatic and inflexible element, inside a slope with a indefinite length ("indefinite slope" Fig. 1[21]).

The force of gravity acts on this element dividing itself in a tangential component (shear strength) and in a perpendicular component that creates friction with an opposite verse to that of shear strength, to which the cohesion of soil particles (shear resistance) has to be added.

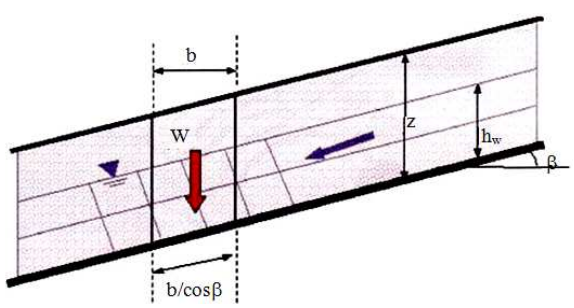

Fig. 1: The indefinite slope[21]

Shear resistance τ is described by Mohr-Coulomb law:

$$\tau' = c' + \sigma' \cdot \tan\varphi' \quad (1)$$

Where:
c' = Effective soil cohesion [kPa]
σ' = Effective stress force that is normal to the slope [kPa]
φ' = Effective angle of shear resistance [°]

When the soil is subject to shear strengths, there is the mobilization of an adding opposition due to the development of tensile strength inside of roots and the whole soil has a greater resistance.

Among the various approaches, the simplified models based on the *equilibrium*-limit of the strengths show a validity confirmed by *in situ* and laboratory studies[17.23]. Through their simplicity, these models can be used both in the evaluation of natural slope stability and in the area of works which will use plants covering. This method is based on the hypothesis that the root is cylindrical, linearly elastic, perpendicular through the critical slip surface and that the shear resistance angle of the soil is not influenced by the roots (Fig. 2).

The shear strength of the roots is divided in a tangential factor (opposed directly to the shear stress) and in a perpendicular factor that increase the normal stress, so Coulomb law becomes:

$$\tau = c' + \sigma_N' \cdot \tan\varphi' + (A_R/A) \cdot T_R \cdot \text{sen}\theta + (A_R/A) \cdot T_R \cdot \cos\theta \cdot \tan\varphi' \quad (2)$$

Where:
c' = Soil cohesion
σ_N' = Stress normal to the shear area
φ' = Angle of internal friction of the soil
(A_R/A) = Relationship of root area
θ = Distortion angle of the root (that is variable) caused by the shear stress
T_R = Tensile strength activated by the root (a passive strength)

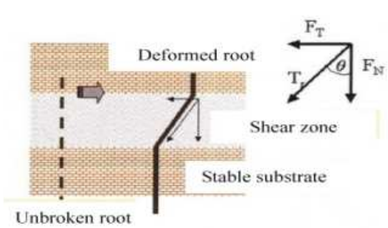

Fig. 2: Model of reinforcement with roots perpendicular to the shear area[6]

Fig. 3: Location map of the study areas: A = Bricherasio (Ghiaie), B = Bricherasio (Belvedere), C = Bibiana

The third addend in the Eq. 2 is referred to a hardly activated strength: in fact the matrix should have a swelling contemporary to the shear displacement.

Regarding this modified Coulomb law, it is clear that the tensile strength of the roots and the shear strength of rooted soil are directly related.

According to the Wu[22] and Waldron[17] model, the root reinforcement depends on many factors: Tensile strength, density and depth of roots that differ in a significant way depending on considered species, local environmental characteristics and spatial variability of vegetation properties. In particular, root density shows an extremely high variability in the space, both in the vertical and in horizontal planes.

Area description: *In situ* tests were realized in three pilot sites situated in Italian Alpine environment, Pellice Valley, in the west of Piedmont (Fig. 3): Two sites are located in the municipality of Bricherasio ("Ghiaie" called Site A and "Belvedere", Site B), one in the municipality of Bibiana (Site C). These sites were selected for the shear tests as being representative of the range of soils in the environment and were studied both in the main chemical physical, biological parameters and in mechanical properties (Table 1 and Fig. 4-6).

Pellice river runs Pellice valley and is a left-hand tributary of the Po river. Most of the slopes (in particular in the lower part) are dominated by till deposits, that consist of Late Pleistocene and Holocene till deposits, detrital sediments, alluvial deposits, landslides, with a thickness of 10-30 m. Greenstones schist, mica schist and gneiss are the dominant lithotype outcropping.

In the last twenty years, the mean annual precipitation measured in this part of basin is equal to 1.092,3 mm[19]. Precipitation mostly occurs as snowfall from November to April in the upper part of the valley and generally as rainfall in spring and autumn, with a maximum in May and September.

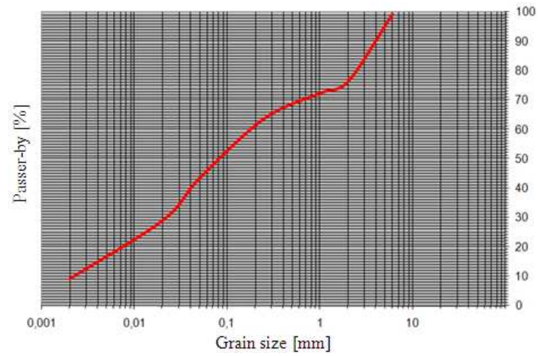

Fig. 4: Grain size in Site A (Bricherasio-Ghiaie)

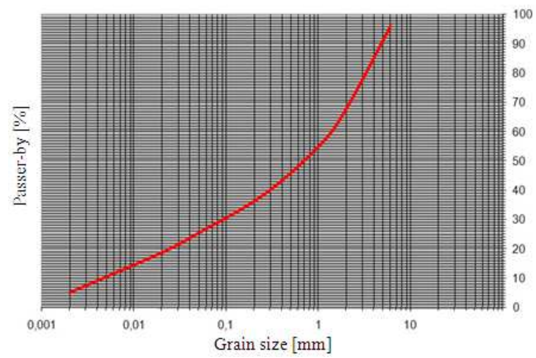

Fig. 5: Grain size in site B (Bricherasio-Belvedere)

Table 1: Site description for *in situ* shear tests (depth: 0-150 mm)

	Site A	Site B	Site C
Site geographic coordinates:			
Latitude N	44°49' 10"	44°49' 35"	44°47' 50"
Longitude E	7°19' 07"	7°18' 10"	7°16' 41"
Altitude [m MSL]	357	402	437
Physical characteristics of the site soil (depth: 0-150 mm):			
Gravel (%)	24	32	21
Sand (%)	33	42	36
Silt (%)	34	20	43
Clay (%)	9	6	0
USC classification	SM	SW	SM
pH	7,6-subalkaline	< 5.5-peracid	5,4-peracid
Plasticity index	91,79-strongly plastic	80,05-strongly plastic	37,71-very plastic
Test 1:			
Mean moisture content	48,88%	31,20%	36,16%
Grass species	*Festuca pratensis* *Lolium perenne* *Poa pratensis*	*Festuca pratensis* *Lolium perenne* *Poa pratensis*	*Festuca pratensis* *Lolium perenne* *Poa pratensis*
Test 2:			
Mean moisture content	23,06%	-	28,47%
Grass species	*Medicago sativa* *Trifolium pratensis* *Lotus corniculatus*	-	*Medicago sativa* *Trifolium pratensis* *Lotus corniculatus*

In these sites *Festuca pratensis*, *Lolium perenne* and *Poa pratensis*; later *Medicago sativa*, *Trifolium pratensis*, *Lotus corniculatus* has been seeded. The amount of seeds has been chosen in according with the agronomic requirements of each species[28]. No fertilizers has been added. Each site had a total surface of about 50 m^2.

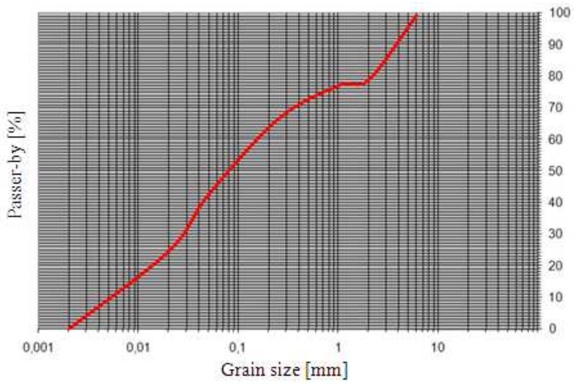

Fig. 6: Grain size in Site C (Bibiana)

MATERIALS AND METHODS

Two sets of *in situ* shear tests were performed (in not drained conditions): the first one during June 2007 with the *Poaceae* the second one during April 2008 with the *Fabaceae* (Table 2).

An equipment was created for providing accurate and reliable information and simulating a shallow translational failure down to a depth of 100, 200 and 300 mm, according the Authors' will.

A sheet frame was designed and constructed. A shear box can run along two guide rails and an hydraulic jack (driven by a power plant) was seated between the box and the frame. The sheet frame is 1200 mm long and 660 mm large; the shear box measures 300×300×100 (or 200, 300) mm deep (Fig. 7 and 8). A load cell (located between the axis and the hand-powered jack) and a slide-wire potentiometer were used to quantify the force needed to shear the soil sample and its displacement. A steel plate with guide rails and the same method of slipping of the shear box was made for measuring the basal and the lateral root resistance. Lubricating oil was put along the guide rails for reducing the friction with the shear box (highest values of friction: 2% of the strength acquired by the load cell). All the system was made closed to the soil with 4 pile shoes, 900 mm long.

The shear surface was imposed at a depth of 0,1 m. The speed trials was controlled by the power plant: In every trial the oil pressure for the hydraulic jack was carefully increased from 0 bar to a maximum of 10 bar.

The trials were made eight months after the seeding: Generally they were 12 trials/specie for what concern the measure of basal resistance, 3 trials/specie for what concern the value of lateral and basal resistance.

Fig. 7: Shear test apparatus set up for the experiments: The sheet frame, closed to the soil with 4 pile shoes; the shear box push up by the hydraulic jack; the load cell and the slide-wire potentiometer

Fig. 8: Particular of the shear test apparatus (shear box and load cell)

Table 2: Description of the tested species during *in situ* shear tests

Species		Characteristics
Poaceae	*Festuca pratensis*	Cold resistant, sensible to dryness and high temperature, bears inundation for long period, excellent for cut and for pasturing, soil ph included between 5,5 and 6,5
	Lolium perenne	Sensible to dryness and high temperature, sensible to coldness, bears high moisture in the soil, soil ph included between 6 and 7
	Poa pratensis	Very slow in the germination, high resistance except during high temperature in the summer period, when it is in the vegetative rest, demanding of water, soil ph included between 6 and 7
Fabaceae	*Medicago sativa*	Bears dryness and high temperature, cold sensitive only at the beginning of his growth, sensible to the water stagnation, not suitable to unconsolidated soil poor of potassium and limestone, soil ph included between 6,5 and 8 (not acid)
	Trifolium pratensis	Needs wet soil and sunlight, sensible to dryness and high temperature, more resistant than *Medicago Sativa* to the coldness, suitable to superficial soil, soil ph about 6
	Lotus corniculatus	Bears wet soil and dryness for long period, suitable to superficial and clay soil, optimal soil ph 6,5 (but it resists until 5)

Some trials were considered not correct for external factors (presence of gravel or old roots into the soil, bad function of the data recorder for the air moisture…). All the valid tests made with the *Fabaceae* are shown in Table 4. The trials made with the *Poaceae* are used in association: In Table 3 there are the average data.

Table 3: Average data results acquired in Test 1, June 2007

Site	Grass species	Shear time [sec]	Peak shear strength [kPa]	Shear displacement [mm]	Root area [%]	Average increase in peak shear strength due to roots [%]	Average increase in displacement due to roots [%]
Site A	non rooted	33,5	1,2	10,0			
	Festuca pratensis	40,0	5,1	24,9	0,024	325,0	16,4
	*Festuca pratensis***	56,1	11,7	67,0		875,0	213,1
	Lolium perenne	86,6	4,4	57,3	0,012	266,7	167,8
	*Lolium perenne***	77,8	10,5	72,2		775,0	237,4
Site B	non rooted	21,8	1,9	25,8			
	Lolium perenne	22,4	9,4	12,0	0,008	394,7	-53,5
	*Lolium perenne***	18,7	10,9	15,0		473,7	-41,9
Site C	non rooted	20,7	8,2	9,2			
	Festuca pratensis	80,0	12,3	16,3	0,020	50,0	77,2
	*Festuca pratensis***	125,7	17,8	49,5		117,1	438,0
	Lolium perenne	155,7	20,4	37,8	0,026	148,8	310,9
	*Lolium perenne***	92,1	20,8	47,3		153,6	414,1

**: Measured basal and lateral resistance

Table 4: Data results acquired in April 2008

Name of the area	Grass species	Shear time [sec]	Peak shear strength [kPa]	Shear displacement [mm]	Root area [%]	Average increase in peak shear strength due to roots [%]	Average increase in displacement due to roots [%]
Site A	Non rooted-average	3,2	7,8	1,1			
	Medicago sativa	5,4	11,3	42,2	0,07	19,2	1.688,9
		6,0	14,3	31,0			
		7,4	10,5	50,0			
		4,0	5,6	32,4			
		6,8	12,2	35,8			
		3,2	4,2	24,5			
		3,6	7,2	22,1			
		5,4	11,0	24,1			
		8,4	8,0	48,6			
		3,6	8,6	11,7			
	Average	5,4	9,3	32,2			
	*Medicago sativa***	8,4	17,1	18,7		84,6	1.166,7
		8,2	13,1	28,4			
		7,0	13,1	21,2			
	Average	7,9	14,4	22,8			
	Trifolium pratensis	6,4	7,1	55,1	0,03	20,5	1.900,0
		9,6	12,6	71,2			
		5,4	8,5	39,2			
		7,4	5,7	42,9			
		3,2	6,3	13,5			
		4,2	7,4	24,2			
		3,6	12,6	22,9			
		4,0	15,3	19,2			
	Average	5,5	9,4	36,0			
	*Trifolium pratensis***	12,0	12,4	46,3		67,9	2.433,3
		10,6	11,6	55,6			
		12,4	15,2	35,0			
		11,7	13,1	45,6			
Site A	*Lotus corniculatus*	5,6	10,3	25,7	0,10	55,1	794,4
		3,6	16,0	19,9			
		5,4	22,5	25,1			
		1,4	4,9	6,2			
		4,4	15,9	23,1			
		3,4	12,4	17,2			
		2,4	12,7	12,3			
		2,0	7,4	9,4			

Table 4: Continued

		4,2	7,1	12,2			
		3,2	11,7	9,3			
	Average	3,8	12,1	16,1			
	*Lotus corniculatus***	5,6	16,1	21,2		114,1	1.016,7
		6,0	17,3	10,9			
		9,6	16.7	28.2			
	Average	7,1	16,7	20,1			
Site C							
	non rooted-average	1,5	4,8	2,0			
	Medicago sativa	2,2	10,1	12,1	0,007	134,8	493,5
		2,6	11,0	11,1			
		2,8	12,1	9,8			
		2,2	13,6	10,6			
		4,6	8,8	31,2			
		5,4	14,3	19,2			
		4,2	12,3	6,3			
		2,2	11,3	5,6			
		1,8	7,8	1,5			
	Average	3,1	11,2	11,9			
	*Medicago sativa***	3,0	11,8	19,8		116,8	643,3
		4,4	11,0	15,1			
		2,2	8,2	9,9			
	Average	3,2	10,3	14,9			
	Trifolium pratensis	4,6	12,3	19,1	0,01	124,5	793,0
		3,8	12,7	17,2			
		4,8	5,6	20,7			
		4,0	9,5	20,7			
		3,2	5,6	17,8			
		3,4	10,6	20,7			
		4,4	12,6	16,3			
		5,0	10,6	25,9			
		3,2	10,8	14,0			
		3,8	11,1	17,1			
		2,2	13,4	13,0			
		3,6	13,7	12,9			
	Average	3,8	10,7	17,9			
	*Trifolium pratensis***	4,8	17,5	21,9		169,6	920,9
		4,4	12,0	15,2			
		4,6	9,1	24,4			
	Average	4,6	12,9	20,5			
	Lotus corniculatus	5,2	14,3	19,0	0,03	166,2	765,1
		4,2	11,7	18,7			
		4,0	8,7	17,1			
		8,0	17,3	17,0			
		5,2	12,4	12,5			
		4,8	13,7	15,0			
		4,8	10,2	25,5			
		4,8	12,8	18,8			
		2,8	15,4	13,3			
		6,8	16,3	29,6			
		2,6	10,9	9,1			
		3,4	8,6	13,1			
	Average	4,7	12,7	17,4			
	*Lotus corniculatus***	8,2	14,7	32,8		192,2	1.305,5
		8,6	13,9	34,8			
		5,6	13,2	17,1			
	Average	7,5	13,9	28,3			

**: Measured basal and lateral resistance

RESULTS

The trials were influenced by the depth of the shear surface, the soil moisture and the different period passed from the seeding to the test. The results obtained in the shear tests made with rooted samples are compared directly with the data of soil in absence of roots, acquired in the same day and in the same place (they were considered the landmark).

The resulting curves for non-rooted and rooted samples was compared and it was noted shear time, peak shear resistance, shear displacement, root area, soil moisture and average increase in peak shear strength and average increase in displacement due to roots are calculated (Table 3 and 4).

Test 1-June 2007: These tests were made during and after rainfalls, situations similar to those before the generation of a slip landslide on a mountain slope.

Observing the graph of data acquired (Fig. 9 and 10), the trend is similar to a line and it can be easily recognized the point of the shear strength , the time and its respective shear displacement.

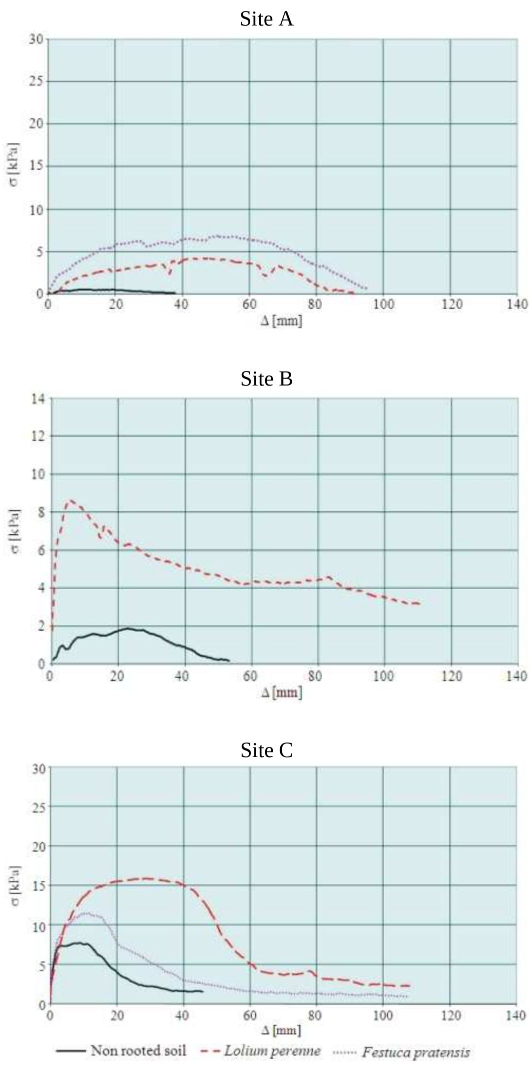

Fig. 9: Typical measured shear stress Vs shear displacement for the three test site. Comparison between non rooted soil and rooted soil with *Lolium perenne* and *Festuca pratensis* (June 2007)

In the rooted samples, the shear plane was observed to assume a level form beneath the shear box: this is due to the fact that the system weight is widely enough for these sort of tests.

Root area: After the trials the Authors evaluated the root area (i.e., the diameter of the roots that cross the shear plane) with the use of a gage. In this way, it can be estimated the tensile strength of every specie and its adaptableness with the Alpine soil.

Seeing Table 3, it can be seen that *Lolium perenne* is the *Poaceae* with the highest value of root area in the 3 sites (0,026%, Site C); *Festuca pratensis* grew up better in Site A. The worse results is given by *Poa Pratensis*, that did not develop in all the soils used, for soil properties and weather conditions not favorable.

Site A: The soil moisture had a high value: 48,88%.

In this site the rooted samples showed a mean increase in peak shear strength over the non-rooted samples change from 266,7% (*Lolium perenne*) to 325% (*Festuca pratense*).

The value of the root area were comprised between 0,012% (*Lolium perenne*) and 0,024% (*Festuca pratensis*) and in every shear test the roots were unthreaded, almost never broken. This fact proved that only a part of the tensile strength of the single root was mobilized and this happened because the roots were several with a small diameter. So the friction with the grain soil is low.

The average increases in displacement due to roots were always positive: The value were included between 25 mm (*Festuca pratense*, 16%) and 57,3 mm (*Lolium perenne*, 237%).

Observing the data obtained from tests that measured basal and lateral resistance, a great increase in peak shear strength in rooted clods with *Festuca pratensis* and with *Lolium perenne*: The value obtained was of 875 and 775% respectively. The fasciculate roots incorporated a great soil surface their friction with the soil became higher.

Site B: The number of tests that could be carried out was limited by a dry winter. The chemical and physical soil characteristic do not permit the development of the species planted, consequently the shear tests data are less if compared which other sites . Lolium perenne was the specie that survived The soil moisture had a ratio value of 31,20% (low even with the rainy days).

The trials gave results different one from another. There was an increase in peak shear strength (395% is the percentage increase in the basal resistance), but a decrease in displacement (-53% respect to the non-rooted sample).

Site C: In this site the moisture in the soil had value of 36% due to high presence of silt (43%). The rooted samples had an increase in shear resistance (4,1 kPa the average increase for the *Festuca pratensis*, 12,2 kPa for the *Lolium perenne*). For rooted samples the maximum shear resistance coincided with a greater displacement: The increase was 16,3 mm for the *Festuca pratensis* (77%) and 37,8 for the *Lolium perenne* (311%).

Root area was greater than one estimated in Ghiaie: 0,02% for *Festuca pratensis* and 0,026% for *Lolium perenne*.

TEST 2-April 2008: The test developed in this month were made after spring rain event, but less persistent than the past year: So the moisture in the soil had value of 23,1% in Site A and 28,5% in Site C. These values influenced in particular the tests made in Site A in non rooted soil because the included gravel had a superior resistance in a drier soil (greater friction among the particles): In fact the results were increased of four times than those obtained in 2007. The site B has been abandoned because of the previously unsatisfactory results.

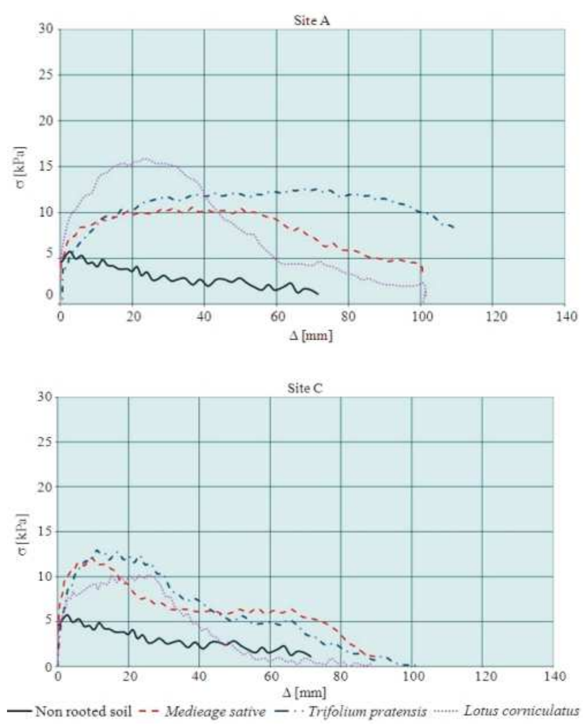

Fig. 10: Typical measured shear stress Vs shear displacement for the two test site. Comparison between non rooted soil and rooted soil with *Medicago sativa*, *Trifolium pratensis* and *Lotus corniculatus* (May 2008)

Root area: As it can be shown in Table 4, *Lotus corniculatus* is the *Fabaceae* and in general the grass specie with the highest value of root area in the sites (0,1%, Site A); *Medicago sativa* showed the worse value (0,007%, Site C).

Site A: *Medicago sativa* increased the strength of 19,2% (9,3 kPa-the worse increase among the *Fabaceae*) and the displacement of 1688.9%. *Lotus corniculatus* showed a massive development of the roots (root area = 0,102%) and the best results in strength increase: 55,1% (12,1 kPa). *Trifolium pratensis* increased the strength of 20,5% and the displacement of 1.900% (36,0 mm-the best increase).

The data obtained from tests measuring basal and lateral resistance (*Medicago sativa* 84,6%; *Lotus corniculatus* 114,1%; *Trifolium pratensis* 67,9%) showed values that grew up in proportion with those acquired in the tests measuring basal resistance.

Site C: *Medicago sativa* and *Trifolium pratensis* showed very similar values in peak shear strength (11,2 kPa and 10,7 respectively) and root area (0,007 and 0,01%). The great difference lives in the shear displacement: The root of *Trifolium pratensis* had a lateral growth and reached an average result of 17,9 mm, *Medicago sativa* had a vertical growth and reached an average of 11,9 mm.

Lotus corniculatus showed good attitude to grow in a humid area. For this reason it present an high value in root area (0,030%) and in the increasing in shear strength (166,2%).

DISCUSSION

The results obtained from the trials (Fig. 11-16) are important because implement the data regarding in situ shear test. It is not possible carried to have a formula and or equation to explains and describe contribution of grass roots on the shear strength of soils, because each species has its mechanical properties. According with Normaniza et al.[24] the great variability in shear strength is due to many factors: Particle-size compositions of the soils tested, chemical and physical characteristics, densities, moisture and cohesion with the roots[25], the presence of voids (that, for example, gives greater displacements before reaching the peak shear resistance), old roots in the soil non-uniform distribution of the roots.

Despite the variability of the data, the rise in shear resistance, as displacement increases, is self-evident in rooted samples. The point of peak shear resistance has been measured quite easily using the apparatus proposed.

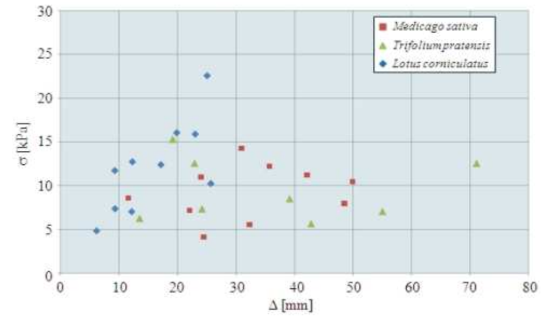

Fig. 11: Variation of the measured peak shear strength Vs peak shear displacement of every single trial for *Medicago sativa*, *Trifolium pratensis*, *Lotus corniculatus* Test June 2007, Site A

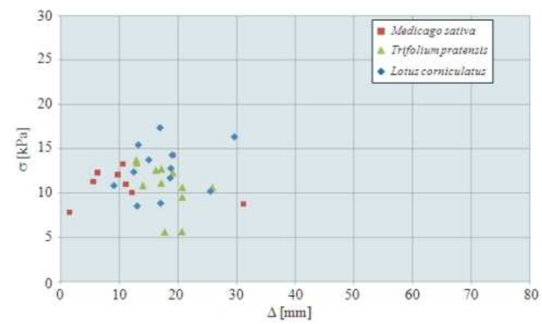

Fig. 12: Variation of the measured peak shear strength Vs peak shear displacement of every single trial for *Medicago sativa*, *Trifolium pratensis*, *Lotus corniculatus* Test June 2007, Site C

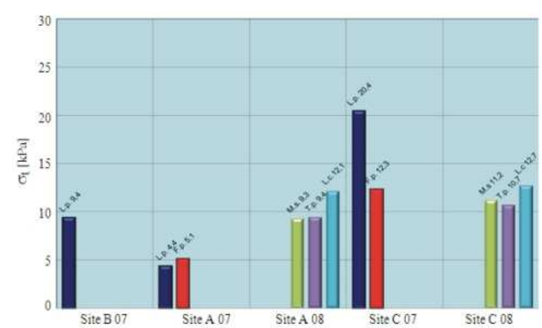

Fig. 13: Average peak shear strength-basal resistance (L.p.: *Lolium perenne*; F.p.: *Festuca pratensis*; M.s.: *Medicago sativa*, L.c.: *Lotus corniculatus*, T.p.: *Trifolium pratensis*)

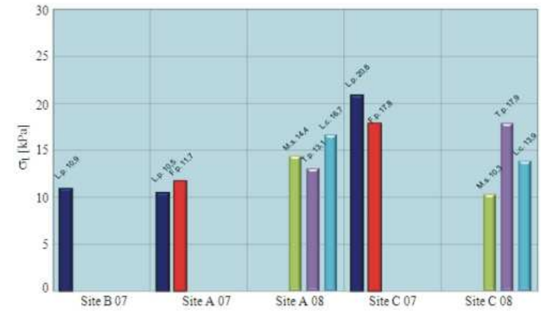

Fig. 14: Average peak shear strength-basal and lateral resistance (L.p.: *Lolium perenne*; F.p.: *Festuca pratensis*; M.s.: *Medicago sativa*; L.c.: *Lotus corniculatus*; T.p.: *Trifolium pratensis*)

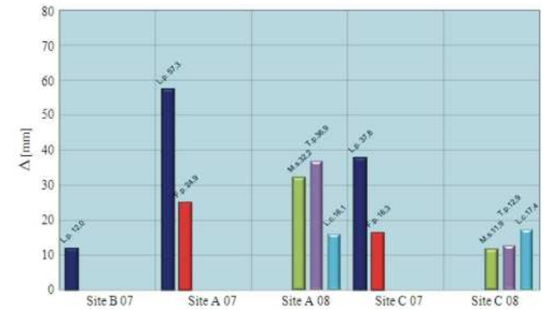

Fig. 15: Average shear displacement-basal resistance (L.p.: *Lolium perenne*; F.p.: *Festuca pratensis*; M.s.: *Medicago sativa*; L.c.: *Lotus corniculatus*; T.p.: *Trifolium pratensis*)

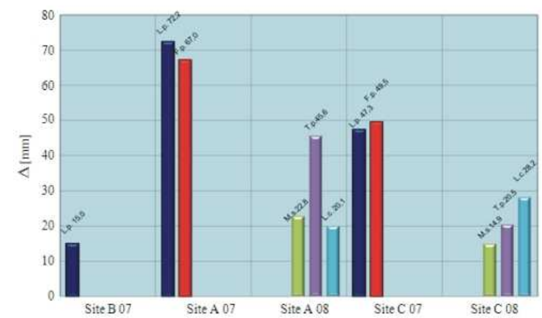

Fig. 16: Average shear displacement-basal and lateral resistance (L.p.: *Lolium perenne*; F.p.: *Festuca pratensis*; M.s.: *Medicago sativa*; L.c.: *Lotus corniculatus*; T.p.: *Trifolium pratensis*)

A feature in the shape of many of the curves of rooted samples is a gradually increasing shear resistance, with a first part that represents the soil shear strength (and the soil becomes more compact-in according with Tosi[26]); second, there is a slightly variation of the slope of the curves, that becomes a little steeples (the roots tensile strength is mobilized). The rise in shear resistance stops when a plateau is reached, representing the maximum shear resistance by the rooted material. The peak shear resistance occurred at a greater displacement for the rooted samples than the non-rooted ones and the soil slipping happened in a longer time. This process was identified by Wu and Watson[3].

The results concerning the residual shear strength demonstrate that it is slightly greater for rooted soils than non-rooted[19]. When the roots failed, they kept the soil still packed together and they avoid its breaking up.

In addition, it is significant to evaluate the attitude of these grass species reading the results shown in Fig. 11 and 12. In site A, the shear strength reached higher values than those yielded in site C. In particular *Lotus corniculatus* trials are collected in the first part of diagram, with high shear strength values (22,54 kPa was the maximum) and low shear displacement values (included between 6,20 and 25,74 mm): It grew up with ease, in the natural weather condition found in the two site, but its roots are very small. *Medicago sativa* data is placed in the central part, without reaching high values neither in shear strength (4,16 ÷ 14,27 kPa) nor in displacement strength (11,67 ÷ 49,96 mm): its roots are the greatest in size and they reached the depth of about 30 cm, but they were not many. *Trifolium pratensis* show the highest shear displacement values (until 71,18 mm): it had a root area included between the values of the two other species (0,03%).

In site C the results are pulled together with lower values of shear displacement, because they troubled to develop in presence of other weed species, such as *Lolium* spp. In this area *Medicago sativa* showed a moderate act (peak shear strength: 7,84 ÷ 14,25 kPa; shear displacement: 1,54 mm ÷ 31,17 mm). *Lotus corniculatus* was able to colonize the whole piece of ground and the shear tests with this specie were the best made (16,31 kPa was the maximum).

Evaluating the two set of trials it can be seen that *Fabaceae* had a higher resistance in shear strength (increase the basal resistance until the 325%): The best species was *Festuca pratensis* (peak shear strength: 5,1 kPa) that allowed the growth of native species and, interacting with them, it showed a high percentage augment in peak shear strength. *Lolium perenne* showed an excessive growth in the aerial part, needing its cutting 3 times in 8 months: It was a negative attribute, because this fact underlined that it needs a continue care.

The evaluation of basal and lateral resistance, even if the trials are few, had a considerable augment in all the tested species, except *Trifolium pratensis* and *Medicago sativa*. This is not accidental: they are the only two species that have not fasciculate roots with a lateral development, but able to reach the depth of 30 cm.

CONCLUSION

In situ shear tests on root-reinforced soils were conducted in this research to investigate their influence in the soil shear strength. It was shown that grass roots increase the shear strength of soil, its displacement, delay the phenomenon of soil slipping and the results is more appreciable proportionally to the number of roots that cross the shear plane and their diameters. Recommendation is that soil should be fine enough to enable the roots to adhere strongly to the soil particles, thereby allowing tensile stresses within the roots to be dissipated in the body of the soil. The weak adhesion between the roots and the soil at that site suggests that this energy transfer would not take place effectively in cohesionless soils. Concerning the species tested:

- *Festuca pratensis* and *Lotus corniculatus* show the main mechanical properties respectively for *Poaceae* and *Fabaceae* families
- *Lolium perenne* is not recommended because it showed a great aerial growth, it is weed and is inclined to choke the other grass species
- *Trifolium pratensis* and *Medicago sativa* shows good mechanical properties, but they suffer the local climate condition

Behavior on these consideration in a mix of grass seeds to be utilized for increasing the soil reinforcement it is suggested to include in high percentage seeds of *Festuca pratensis* and *Lotus corniculatus*, in low percentage seeds of *Trifolium pratensis* and *Medicago sativa* and exclude seeds of *Lolium perenne*.

Despite the widen use of vegetation for protecting and stabilizing slopes is spreading, there is the need of clear knowledge of the way in which the roots will act to improve slope condition. It is on purpose to support these results with tensile tests of the single root taken in the sites in the period of the shear tests and to continue these shear tests mixing in different percentage the species tested.

ACKNOWLEDGMENT

The research was financially supported by “Regione Piemonte-CIPE 2004”.

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