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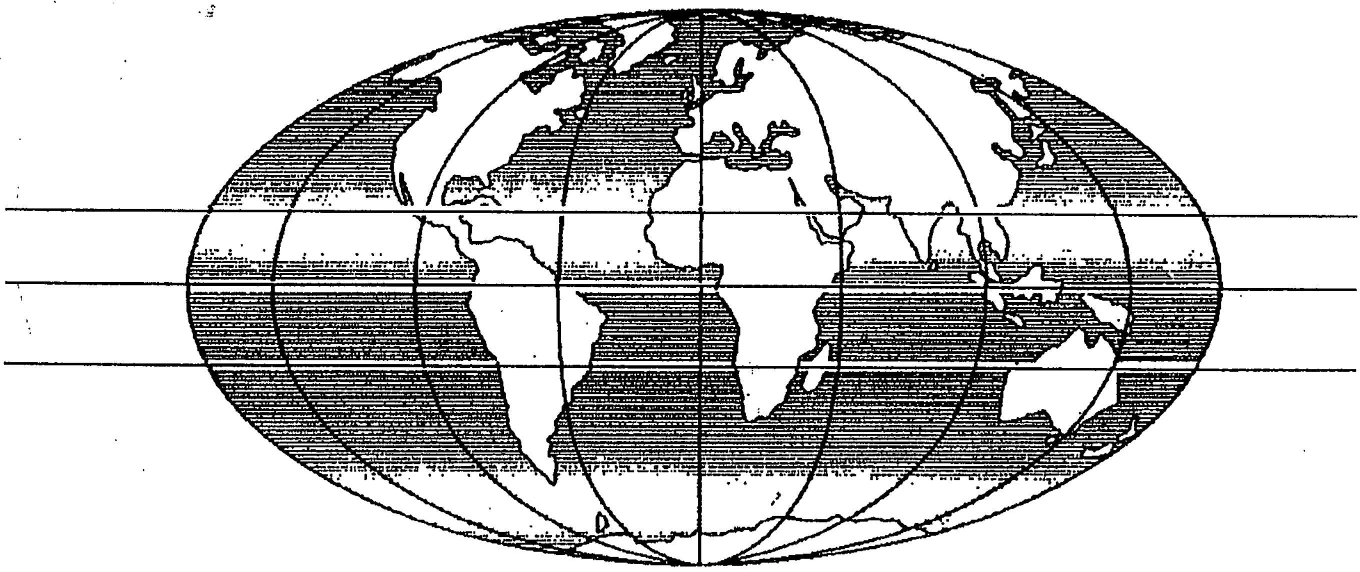

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39 The Effect of Grass Roots on the Shear Strength of Colluvial Soils in Nepal

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1 INTRODUCTION

The Overseas Development Administration has supported a programme of research to assess the forms of instability affecting the slopes on roads built in Nepal under ODA funding, with a view to mitigating the instability at minimal cost. Early trials with wattle fences and locally made erosion blankets failed within a short time, because they were unable to prevent the soil from liquefying and flowing beneath. It was evident that alternative techniques would have to be devised for Nepal's active environment, and that vegetation would have to play a major part in any slope rehabilitation programme in order to minimize costs. Thus, one aspect of the research programme turned to look at the effect of vegetation in improving soil strength (Clark 1992). This chapter discusses a study of field shear testing carried out under the research project.

2 DESCRIPTION OF THE AREA

The geology of the Himalayan foothills consists of mostly sedimentary rock sequences of increasing metamorphic grade from south to north, the grade jumping considerably when each of a series of thrust faults that divide the ranges into well-defined geographical units is crossed. The southern ranges consist of very soft sandstones and mudstone sequences, progressing northwards through a zone of phyllites and quartzites into gneisses. The rocks are often very shattered and are prone to rapid weathering, especially at low altitude, where temperatures are high (average 22°C for the year). The hillslopes lie at an average angle of 35°, steepening locally to 50°. The slopes are mantled with a layer of colluvium 1–3 m thick, overlying soft weathered rock. The colluvium typically consists of mixed rock debris in a matrix of fine material of low plasticity. The bulk density is low, ranging from 1.50 to 2.35 g/cm^3 (average about 1.7 g/cm^3). Both the natural slopes and engineered

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slopes are highly susceptible to erosion and sliding, the latter often of a shallow nature due to saturation by heavy rain.

East Nepal is under the influence of the southwest monsoon. During the four months of June to September some 1500-2000mm of rain falls. Although it may rain for several days continuously, the rainfall pattern usually takes the form of rainy periods of a few hours interspersed by dry spells. If the clouds disperse between showers, the drying effect of the sun upon the top few centimetres of the soil is very strong. Rainfall intensity during cloudbursts that last from a few minutes to a few hours can be up to 100mm/hour or even more. On these occasions the permeable soils take in large quantities of water and can become saturated or nearly so to depths of around 0.25m. This can cause the upper soil layers to begin to move downslope as a plastic or even a liquid mass. After a storm, the water dissipates quickly into the ground and the soil returns to field capacity probably within the space of a few hours at most. The shear tests were carried out in undrained conditions, and the soil moisture content would have been at or a little below field capacity.

The Dharan-Dhankuta road in east Nepal, where the work described in this paper was carried out, lies in the zone of highest rainfall and weathering. The sites selected for the shear experiments were chosen as being representative of the range of soils in the area (Table 1). The grass species on these sites, all clumping grasses, are also local species and are all used in the slope rehabilitation programme. *Pennisetum purpureum* (elephant grass, napier), *Cymbopogon microtheca*, *Themeda* sp. and *Neyraudia* sp. are all clumping grasses of large stature growing to 1.5 or 2m. *Cymbopogon microtheca* has a hemispherical root network extending about 0.5m in all directions from the culm; the central two thirds of the hemisphere are very dense. *Pennisetum purpureum* has a dense mass of unbranched roots about 2mm thick and some 200mm long, each bearing many short, hair-like laterals a few centimetres in length. The architecture of the root systems of *Themeda* and *Neyraudiana* is not known in detail, but they are substantial. *Setaria anceps* and *Imperata* sp. are also clumping grasses, about 0.5m in height.

3 EXPERIMENTAL WORK

Greenwood (1983)[1] identified the principal ways in which vegetation can influence slope stability. These are: modifying pore water pressure, soil reinforcement, increased shear resistance along a potential shear plane, surcharge load on the slope and wind throw. Not all are beneficial, but there is potential benefit in the capacity of roots to increase shear resistance by intercepting a shear plane.

A number of researchers have attempted to model this effect. Wu (1976) developed a model which assumes that roots are elastic and flexible. They extend across the shear plane and develop tension when the root is distorted during shearing. Wu's model assumes that full tensile strength is realised through root-soil bonding or adhesion, which increases the apparent cohesion of the soil. Although some work has been done on the factors that influence the effect of roots on apparent cohesion, very few data exist on the actual increase in shear strength that grass roots can provide. Tobias (1994) demonstrated that the importance of grass roots in

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[1] ERRATUM The reference to Greenwood (1983) should be to Coppin and Richards (1990, p 181). This change has been made in the References.

Table 39.1 Site descriptions for *in situ* shear tests

	Site	Soil	Moisture content at 100 mm depth (%)	Vegetation
Alluvial fan (Ghopa Camp)	Ancient, weathered alluvial fan. Slope of site 5°. (Class: Terai Region; alluvial fan)[a]	Silty clay loam; few stones	23	*Pennisetum purpureum* grass
Quartzite slope (Karkichap)	Colluvial/alluvial slope over shattered quartzite and shale. Slope of site <10°. (Class: Middle Mountain Region; moderate slopes (<30°))	Shallow sandy loam, locally stony	24	*Setaria anceps* grass
Shale slope (Ambote)	Ancient high terrace and colluvium. Slope of site <10°. (Class: Middle Mountain Region; steep slopes (>30°))	Weathered phyllitic shale; Platy; sand 77%;[b] silt 16%; clay 7%	8	Grasses: *Themeda* sp., *Neyraudia* sp., *Cymbopogon microtheca*
Gneiss hill slope (Dhankuta)	Ancient boulder field. Weathered gneiss with high mica content. Slope of site <10°. (Class: Middle Mountain Region; moderate slopes (<30°))	Friable loamy sand, shallow; sand 82%; silt 13%; clay 5%	15	Grasses: *Cymbopogon microtheca; Imperata* sp.

[a] Terrain classes defined in Nelson *et al.* (1980).
[b] Particle-size distribution data from Howell (1988).

contributing to soil shear strength is most pronounced in soft soils, and increases with rising moisture content.

The experiments described below are an attempt to measure shear strength directly in the field, to gain a better understanding of the conditions under which roots can improve soil strength, and when no improvement can be expected. If roots do increase the soil's resistance to shear then the peak shear strength should be higher for rooted soils or should be achieved at a greater displacement of the soil mass along the plane of shear. Also, the decrease in strength from peak shear resistance to residual shear resistance should be more gradual for root-permeated soil.

3.1 Methodology

Standard laboratory and field methods of measuring soil strength all have severe limitations on the coarse, stony soils of low cohesion that typify Nepalese colluvial soils. Furthermore, none of them is able to measure the behaviour of plant roots during soil failure in the field. A field shear box was therefore designed and constructed for the purpose (Figure 39.1). The shear box measures 250 x 250 x 100 mm deep. The base of the box sits at the level of the base of the sample to be tested, in the plane of shear. A hand-powered jack is used to provide the shear force, and a dial gauge and compression force transducer are used to measure the force needed to shear the soil sample. The average rate of displacement was 1 mm/s and the force was measured every 0.5 mm of displacement.

The shear box is easily portable and theoretically can be used on very steep slopes (of around 30°). However, testing on slopes leads to difficulties in controlling the normal load and in the event, tests were carried out on level ground. The field shear box allows *in situ* tests to be carried out on soils both with and without roots. The box is pressed down progressively over a block of soil over which it just fits, to provide an undisturbed field sample. Rooted samples are prepared by placing the box over a grass tussock, the canopy having first been removed to allow the normal load to be applied.

The apparatus can simulate a shallow translational failure down to a maximum depth of about 0.3 m. The maximum displacement possible with this set-up was 35 mm, which proved to be less than the required displacement needed for rooted soils (see subsection 5). The confining stresses used were relatively low (Table 39.2), but they represent overburden pressure equal to shallow surface failure to a maximum depth of 0.8 m.

RESULTS

4.1 Alluvial Fan Site

The most complete results come from the alluvial fan site where the soil contains few stones and where there were plenty of plants to test. The results from this site will be discussed in detail and used as a means of comparing the results from the other three sites. The results of the field tests were analysed in two ways:

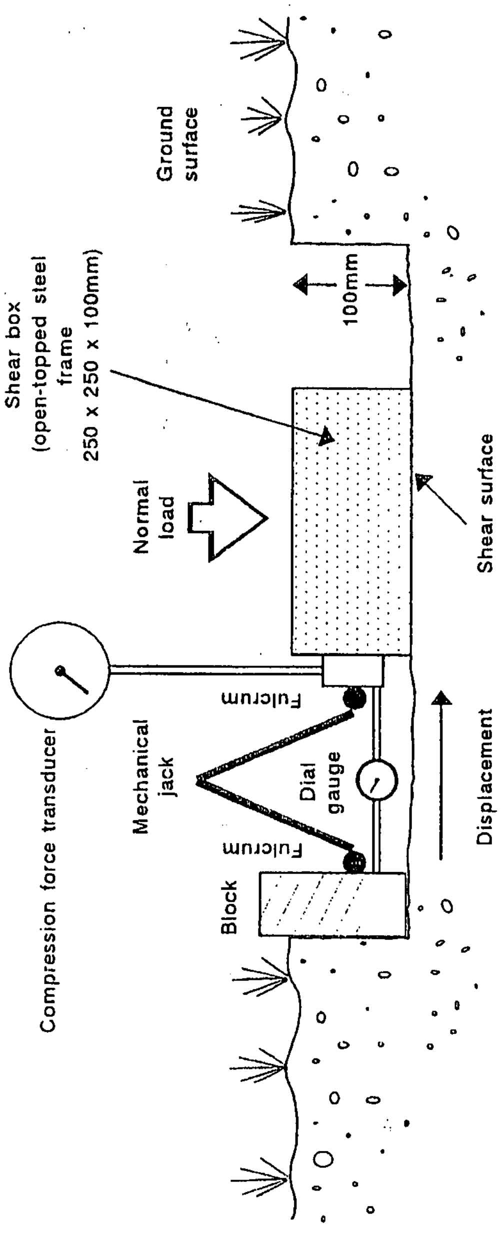

Figure 39.1 Schematic diagram of the shear box used for *in situ* testing

Table 39.2 Peak shear strength of non-rooted and rooted soils

	Normal stress (kN/m²)	Peak shear strength: non-rooted soil (kN/m²)	Peak shear strength: rooted soil (kN/m²)	Increase in peak shear strength due to roots[b] (%)
Alluvial fan (Ghopa Camp)	4.7	10.8	14.6, 10.5, 22.4	35, −3, 107 (46)
	7.8	14.2	12.7, 20.7[a], 25.7	−11, 45, 81 (38)
	10.9	15.2	16.0[a], 20.7[a], 34.4	1, 36, 126 (54)
	14.1	16.0	19.6, 17.2, 27.6	22, 7, 72 (34)
Quartzite hill slope (Karikchap)	4.7	6.5	9.2, 6.8	41, 5 (23)
	7.8	8.8, 7.2	6.4, 8.6	−27, 19 (−6)
	10.9	10.7, 5.6, 12.0	1.4, 9.3	−87, 66 (−44)
	14.1	9.6, 5.2, 11.2	1.3, 7.7	−87, 48 (−48)
Shale hill slope (Ambote)	4.7	6.9	7.9	14
	7.8	9.4	9.3	−1
	10.9	14.0	10.5, 9.4	−25, −33 (−29)
	14.1	13.2	16.8	27
Gneiss hill slope (Dhankuta)	4.7	—	14.9	—
	7.8	11.6	22.3	91
	10.9	13.3	14.8	11
	14.1	20.8	21.4	3

[a] Stress/strain line continuing to rise at point when test was terminated.
[b] Average in parentheses.

1. Individual shear test results for values of stress and strain were plotted and the shape of the curves for non-rooted and rooted samples was compared (Figure 39.2). The peak shear resistance, residual shear and the displacement were noted (Tables 39.2 and 39.3).
2. Normal stress and shear stress at failure were plotted and the best-fit straight line through the points was used to establish the strength envelope (Figure 39.3).

The general characteristics of the stress–displacement curves are consistent. The curve rises fairly rapidly but then slackens off into a gently convex peak representing the peak shear value. In the non-rooted samples the post-peak shear value declined, but the "residual" shear value is often only a little lower than the peak shear value, presumably because the soil is relatively loose, being in a naturally consolidated state without having undergone artificial compaction. The displacement distance at peak shear is long: 10–30 mm.

The effect of roots is shown well by these tests. At all four normal loads the rooted samples showed an increase in peak shear strength over the non-rooted samples of 5–8 kN/m², an increase of 34–54% (Table 39.2). As the non-rooted soil failed, the curve declined from the peak shear resistance value. For the rooted samples, the resistance usually continued to increase beyond the maximum value of the non-rooted samples. This tends to confirm that even though the soil itself has failed, the roots go into tension and their tensile strength is mobilized. In all the rooted samples the shear resistance remained at a higher level for longer. The residual strength never seemed to reach a constant value, implying that the roots were still

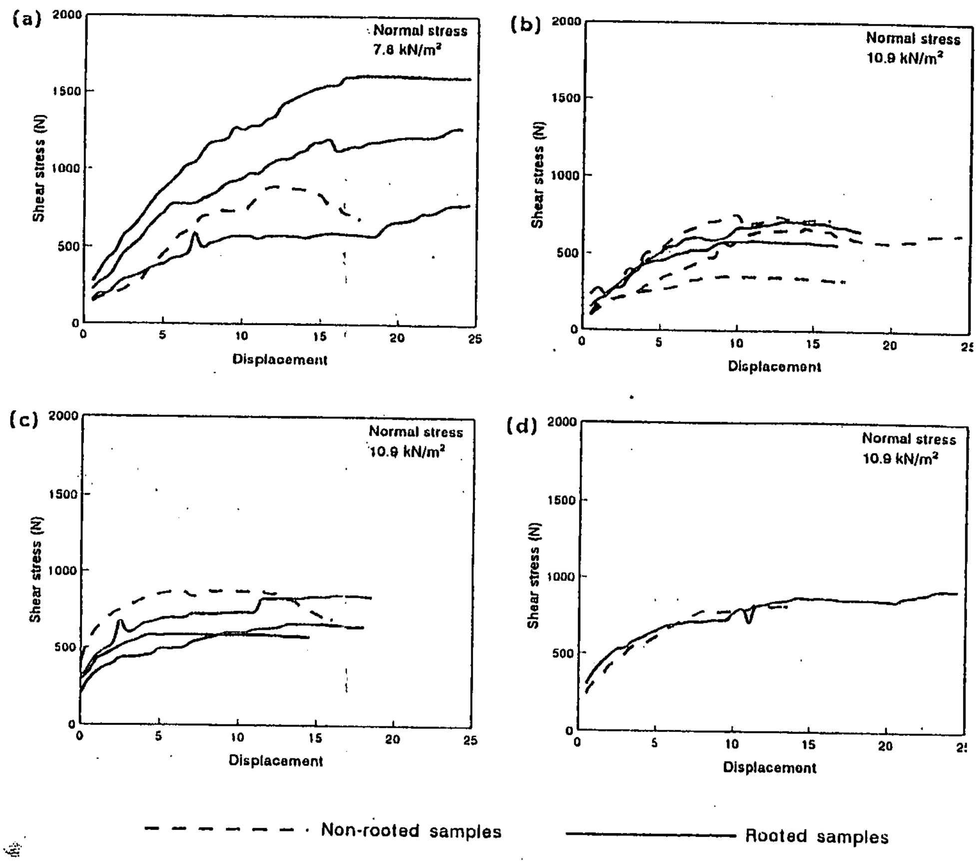

Figure 39.2 Representative stress–displacement curves from the four test sites. (a) Alluvial fan; (b) quartzite hillslope; (c) shale hillslope; (d) gneiss hillslope

resisting shear even at the maximum displacement of 34 mm. At the end of the shear tests, intact roots were found to be still crossing the shear plane, preventing the shear box from being lifted clear. These roots were difficult to pull out: they have a high tensile strength and good adhesion to the soil afforded by the numerous lateral roots. When the roots did fail, they gave way by stripping of the lateral roots from the main root, which then pulled out of the soil. The shear strength envelopes (Figure 39.3) show a very small apparent rise in the angle of internal friction, which would be due to the roots pulling out of the soil. The increase in shear strength of 5–8 kN/m^2 accords with a value of 3–5 kN/m^2 from a similar experiment quoted by Barker in Hewlett *et al.* (1987) for grass on a boulder clay embankment.

The rooted samples generally showed an increase in displacement over the non-rooted samples before peak shear strength was achieved (Table 39.3), although one result shows a shorter displacement. The average increase in displacement between the point of peak shear in non-rooted soil and rooted soil is 5.4 mm, an increase of 49%. The increase in displacement shows the attenuation effect of the roots.

Table 39.3 Displacement distance at which peak shear strength is developed in non-rooted and rooted soils

	Normal stress (kN/m^2)	Displacement: non-rooted soil (mm)	Displacement: rooted soil (mm)	Displacement increase	
				(mm)	(%)
Alluvial fan (Ghopa Camp)	4.7	10.5	21.8	11.3	108
	7.8	12.0	18.5	6.5	54
	10.9	21.0	17.0	−4.0	−19
	14.1	14.0	21.7	7.7	55
Quartzite hillslope (Karkichap)	4.7	7.0	7.7	0.7	10
	7.8	6.0	8.0	2.0	33
	10.9	11.0	11.7	0.7	6
	14.1	11.7	19.2	7.5	64
Shale hillslope (Ambote)	4.7	3.5	6.5	3.0	85
	7.8	12.5	14.0	1.5	12
	10.9	14.0	13.0	−1.0	−7
	14.1	11.0	15.5	4.5	41
Gneiss Hill slope (Dhankuta)	4.7	—	14.5	—	—
	7.8	5.0	24.5	19.5	390
	10.9	8.0	14.0	6.0	75
	14.1	11.5	24.0	12.5	109

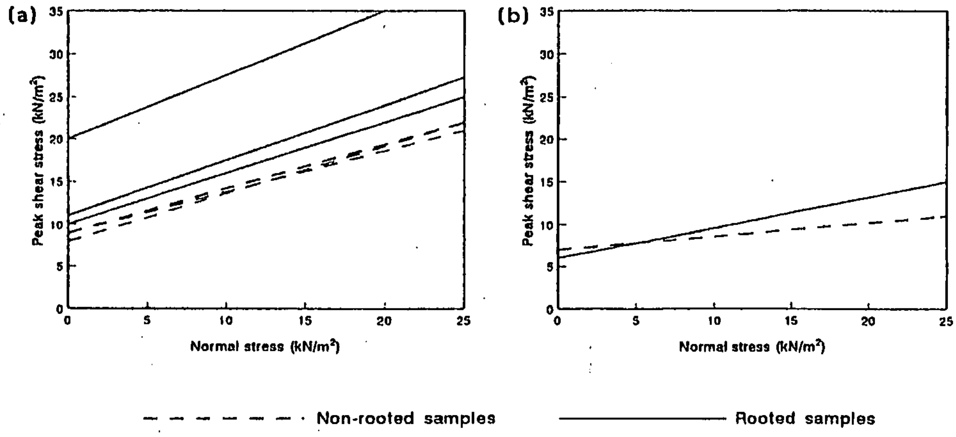

Figure 39.3 Shear strength envelopes for two sites. (a) Alluvial fan (three replicates); (b) quartzite hillslope

In the rooted samples, the shear plane was observed to assume a concave form beneath the shear box. This is presumably due to the fact that the presence of roots forces the shear path downwards to a plane of minimum resistance. The phenomenon would help to explain the apparently low contribution of the roots to increased shear strength, because along the shear plane the density of roots is relatively low.

4.2 Quartzite Slope Site

The number of tests that could be carried out was limited by the very shallow and stony soil. The character of the curves is similar to those from the alluvial fan site, but the curves differ from the alluvial fan samples in showing no obvious reduction in strength after the maximum in either the non-rooted or rooted samples.

The results show very little difference in shear resistance between the rooted and non-rooted samples (Table 39.2), nor in the strength envelopes (Figure 39.3). The displacement results (Table 39.3), however, do show a substantial increase in displacement to peak shear resistance for the rooted soils in all cases, averaging 28%. On this site, a well-watered nursery location, the grass roots were not deep enough to pass across the shear plane, and therefore could not influence shear resistance.

4.3 Shale Site

Again, the number of tests at this site was limited by the shallow soils, and as before, plots of the shear resistance between non-rooted and rooted soils are not significantly different. Peak shear strength does appear to occur at a greater displacement in the rooted soil (Table 39.3). The platy and non-cohesive nature of the soil is such that, even with deep-rooting plants, the adhesion between root and soil is very low. On examination after testing, the soil fell away from the roots. Also, the roots tend to follow a more or less horizontal pathway between the phyllite plates, therefore they are not preventing the plates from sliding over each other.

4.4 Gneiss Site

The gneiss site is characterized by shallow and stony soils, strewn with boulders, which severely limited the possibilities for finding shear test sites. The results in Table 39.2 and 39.3 are given only for comparison with the results from the other sites. Only one sample showed a significant increase in shear resistance due to the presence of roots, although in all the tests the maximum shear resistance occurs at a greater displacement under the rooted samples compared with the non-rooted.

5 DISCUSSION

The results show that there is no universal effect of grass roots on the shear strength of the soils tested. Generally, variability both within and between the sites tends to mask any patterns. This variability is probably due to the different densities of the soils tested and the stoniness of the sites. Also, density within each sample would vary randomly. Variations in density would cause a non-uniform build-up of resistance to shear as particles in denser and less dense areas become rearranged. Bulk density influences directly the point at which peak shear resistance occurs. The presence of voids allows for greater displacement before the peak shear is obtained. Hence, the number of voids will influence displacement at peak shear, irrespective of whether the soil contains roots or not. Any roots will be distributed non-uniformly, and there will be variability in the extent of root contact with the soil. Soil moisture content varies also – a factor that could not be controlled for these experiments.

Some variability may have arisen as a result of the methodology used. The shearing force was applied manually, at a relatively fast rate. This may have led to an uneven application of shear stress, which will affect results. Also, it has been noted that at relatively low normal loads, as used here, variability of results tends to be greater than those obtained under higher confining stresses. However, an increase in applied normal load would not have been representative of the conditions of *shallow* slope instability under investigation. Variability of results is normally offset by increasing the number of replicates. Unfortunately, this was not possible due to the inconsistent nature of the sites.

Despite the variability of the data, overall trends can be discerned. In all cases, the rise in shear resistance as displacement increases is clear for both non-rooted and rooted samples, although the point of peak shear resistance is often poorly defined, presumably due to the unconsolidated nature of the material. Lack of a clear peak shear resistance can also be explained partly by the fact that not all roots reach maximum tensile strength at the same time. The point at which they fail is determined by the characteristics of the roots as well as those of the soil. As these characteristics vary from test to test, the peak shear resistance will be distributed over a range of displacements, another potential source of variability in the results.

A feature in the shape of many of the curves of rooted samples is a gradually increasing shear resistance (representing the soil shear strength being mobilized first), followed by a plateau as the soil reaches maximum shear strength. At this point, the roots' tensile strength is mobilized, resulting in another rise in shear resistance, followed by a second plateau, representing the maximum shear resistance by the rooted material.

Overall, the peak shear resistance occurred at a greater displacement for the rooted samples than the non-rooted ones. This attenuation effect is the most consistent characteristic in the data, more marked than either the increased magnitude of the peak shear resistance or the residual shear values for the rooted over the non-rooted samples. The implication of this is that for any given storm event, rooted soils take longer to fail than non-rooted ones, as greater displacement of material is needed.

As far as comparative residual shear strength is concerned, the results are limited. It might be expected that residual shear strength for rooted and non-rooted tests would be approximately the same once the roots have failed, as all that is left is the shear strength of the soil itself. This is not evident from the present results. At the alluvial fan site the residual shear resistance for the rooted samples was never obtained, as shown by the failure of the stress curves to fall off at a steady rate or to approximate the residual shear strength observed for the non-rooted soil. This suggests that the maximum displacement possible with the existing shear box is not sufficient for shear testing in the field.

The results do show the importance of the rooting depth relative to the shear plane. The lack of difference between results from the rooted and non-rooted samples at the quartzite site can be explained by the fact that the rooting depth of the vegetation was much shallower than the shear plane. Also, if roots develop parallel to the shear plane they may never cross it. At the shale site, the rooting pattern was horizontal because the roots grow between the horizontally oriented plates, which would account for the lack of difference between the shear strength characteristics of the non-rooted soils compared with the rooted samples. By growing parallel to potential failure planes, the roots offer little resistance to shear forces. The poor results in comparative shear strength at this site can also be explained by the poor adhesion between the roots and the soil. The roots could be pulled away from the platy material with very little effort.

Another comment relating to the depth of roots and the shear plane is that the presence of roots appears to deepen the shear plane, as evidenced by the concave shape of the shear plane at the alluvial fan site. Root density is reduced at depth, therefore shear strength will be less here, and failure will occur preferentially deeper in the soil, rather than nearer the surface where roots are denser. The implications of this are that, in the presence of roots, the shear plane is forced down into a more stable region of the soil where confining stresses are higher, but also that the deeper the shear plane goes, the closer will be the shear strength of the root/soil mass to that of unrooted soil.

6 CONCLUSIONS

This work has demonstrated that the direct shear field test method can be used to obtain fairly reliable results on coarse-textured colluvial soils, although the sites tested were level sites and not steep slopes. The data show a considerable degree of scatter, presumably due to inherent variability in soil texture and soil density, as well as rooting pattern. The results suggest that grass roots by no means always increase the shear strength of soil, although under favourable circumstances they can do so significantly. In order to achieve this, a substantial number of roots must cross the shear plane. It also appears that the 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 very weak adhesion between the roots and the flaky soil particles at the shale site, noted upon excavation, suggests that this energy transfer would not take place effectively in cohesionless soils. The characteristics of low density, open texture and coarseness that typify Himalayan mountain colluvial soils tend not to be favourable to good root reinforcement.

Even though the peak shear resistance may not be greatly increased by the presence of roots, the displacement at which peak shear is developed usually is. The roots attenuate the stress–strain relationship and delay ultimate failure.

The use of vegetation for protecting and stabilizing slopes is on the increase, but planting is usually carried out without clear knowledge of the way in which the plants will act to improve slope condition. A body of information needs to be built up, based on experience and backed up by controlled experimentation, to establish more completely the rooting capabilities of individual species and their effectiveness for slope control in different kinds of soil environments. Only then can plants be satisfactorily included in engineering schedules for site works in expectation of their performing a specific function.

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