Assessing the role of vegetation on soil slopes in urban areas

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Abstract: Vegetation has generally been recognised for its aesthetic landscaping qualities in the urban environment, especially along transportation corridors and for use as noise barriers. The detrimental effects of vegetation are also recognised. Trees and shrubs draw out moisture from the ground through evapotranspiration processes, which leads to the seasonal shrinkage and swelling of clay soils. In adverse climatic conditions, e.g. prolonged hot and dry summers, moisture reduction in clay soils may cause substantial damage to buildings and property.

This paper reports on recent projects and studies in the UK and Europe, including the ECO-SLOPES Project (http://construction.ntu.ac.uk) which investigated and defined the positive roles of vegetation in improving the stability of sloping ground. In urban areas, bioengineering techniques have been applied to combat the problems of soil erosion and the shallow landslides that result in the instability of earthworks on the UK's transport network.

The engineering influences of vegetation including moisture and pore water pressure changes, and root reinforcement effects are assessed and techniques for monitoring these influences discussed. The inclusion of the vegetation effects are demonstrated in routine limit equilibrium stability analysis. It is concluded that the roots of appropriately planted and maintained vegetation are likely to provide a 10% increase in the factor of safety of potential shallow slip surfaces.

A computer based slope decision support system is presented to assist engineers to assess the likelihood of a 'slope' being suitable for bioengineering techniques. The slope decision support system is freely available on the ECO-SLOPES website for users to try and feedback on its applicability.

Résumé: La végétation toujours a été reconnue pour ses qualités d'aménagement esthétiques dans l'environnement urbain, surtout le long des couloirs de transport et comme les barrières de bruit. Il y aussi a eu la reconnaissance répandue des effets nuisibles de végétation. Les arbres et les arbrisseaux rallongent l'humidité du sol par les procédés de evapotranspiration, qui mene au recul et l'accroissement saisonniers de sols d'argile. Dans les conditions climatiques défavorables, par ex. a prolongé des étés chauds et secs, la réduction d'humidité dans les sols d'argile peut causer des dommages substantiels aux bâtiments et à la propriété.

Ce papier fait un rapport sur des projets et des études récents dans le Royaume-Uni et Europe, y compris les ECO-SLOPES Projette (http://construction.ntu.ac.uk) qui a examiné et a défini les rôles positifs de végétation dans améliorer la stabilité de sol en pente. Dans les secteurs urbains, les techniques de génie biologique ont été appliquées combattre les problèmes d'érosion de sol et les glissements de terrain peu profonds qui a pour résultat l'instabilité de remparts sur le réseau de transport de Royaume-Uni.

Les influences d'ingénierie de végétation y compris l'humidité et les changements de pression d'eau de pore, et les effets de renforcement fondamentaux sont évalués de le et les techniques pour contrôler ces influences ont discuté. L'inclusion des effets de végétation est démontrée dans l'analyse de stabilité d'équilibre de limite de routine. Il est conclu que les racines de végétation avec à-propos plantée et maintenue vont en toute probabilité fournir une 10% augmentation dans le facteur de sûreté de surfaces d'erreur peu profondes potentielles.

Un ordinateur a basé le système de soutien de décision de pente est présenté pour aider des ingénieurs pour évaluer la probabilité d'une pente est convenable pour les techniques de génie biologique. Le système de soutien de décision de pente est librement disponible sur le site web de ECO-SLOPES pour les utilisateurs pour essayer de le et les réactions sur sa validité d'application.

Keywords: database systems, earthworks, ecology, environmental urban geotechnics, in situ tests, slope stability

INTRODUCTION

In the urban environment, vegetation is generally utilised along railways, highways, canals, river channels, or on artificially made sloping ground such as mine waste slopes for its green aesthetic landscaping qualities rather than its ability to stabilise soil slopes. Vegetation, especially mature trees, when growing in the 'wrong' environment is known to cause millions of pounds worth of damage to buildings and infrastructure annually. However, these negative aspects of vegetation, i.e., the drawing out of moisture from the soil, can in the right situation be a positive attribute significantly influencing the geotechnical parameters of a particular soil.

Soil bioengineering or using vegetation in civil engineering structures is now an established practice in many parts of the world and is considered a practical alternative to more traditional methods of soil stabilisation such as soil nailing or geosynthetic reinforcement. The use of bioengineering techniques promotes and sustains the life of indigenous vegetation species, reduces costs and employs the local labour force. In the U.K., until recently, relatively little information, of relevance to the civil/geotechnical/environment engineer, was known about the below ground functions and properties of the various types of vegetation. This was mainly due to the difficulties in extracting whole root systems, and the problems of testing plant roots both in situ and in the laboratory for their strength and other mechanical properties. The lack of precise information on plant root properties has possibly discouraged the use of soil bioengineering in the U.K. with civil engineers preferring exact numbers to enable quantification for design to take place. Vegetation has for many years been an unknown quantity in stability analysis and the benefits from the strength of roots and increase in root-soil reinforcement have more often than not been ignored.

Recent research at Nottingham Trent University has advanced what we now know about the properties of vegetation below ground and the application of these properties to routine stability analysis (Greenwood, Norris & Wint 2004; Norris 2005a).

In this paper, the benefits and disadvantages of vegetation in urban areas are discussed. The engineering influences of vegetation are assessed and techniques for monitoring these influences presented. The inclusion of the vegetation effects are demonstrated in routine limit equilibrium stability analysis and applied to two case studies of slopes in London Clay. A computer based slope decision support system is described to assist engineers to assess the likelihood of a 'slope' being suitable for bioengineering techniques.

BENEFITS AND DISADVANTAGES OF VEGETATION IN URBAN AREAS

The perceived opinion of vegetation in urban areas is that it causes significant damage to buildings and transportation infrastructure resulting in high costs. These high costs are more often than not associated with poor management and insufficient knowledge to ensure that vegetation is planted in the right place and maintained in such a way as to prevent infrastructure damage. Problems frequently encountered by poor maintenance and inappropriate sitings of vegetation are:

- amassing of fallen leaves and debris may result in drainage channel blockages and potential flooding;
- wind-blown trees during storms and gales may affect the safety of transportation operations;
- mature trees located too close to foundations leads to ground movements of a seasonal and permanent nature (Building Research Establishment 1987; Biddle 1998);
- root growth may cause pavements to crack through both desiccation and root pressures;
- destruction of retaining walls.

Vegetation in urban areas can however perform an important engineering function as it has a direct influence on the soil, at both the surface and at depth (Table 1). Vegetation promotes both soil stability and protects the ground from soil erosion. It may also be used as barriers to noises and unsightly objects or as screens.

Table 1. Influences of vegetation on the soil (Coppin & Richards, 1990).

Surface	Depth
Protection against wind erosion	Increased water infiltration
Protection against foot traffic	Water uptake by roots
Protection against raindrop impact	Reinforcement of soil by roots
Reduction of surface water runoff	Anchoring and buttressing by taproots
Interception of rainfall	
Protection against erosion by surface water flow	

ENGINEERING INFLUENCES OF VEGETATION

Soil stabilisation and reinforcement on sloping ground is probably one of the least recognised and unquantifiable influences the roots of woody shrubs and trees have on the soil. The engineering influences of vegetation used to stabilise sloping ground are illustrated in Figure 1. The main engineering influences of vegetation are summarised as:

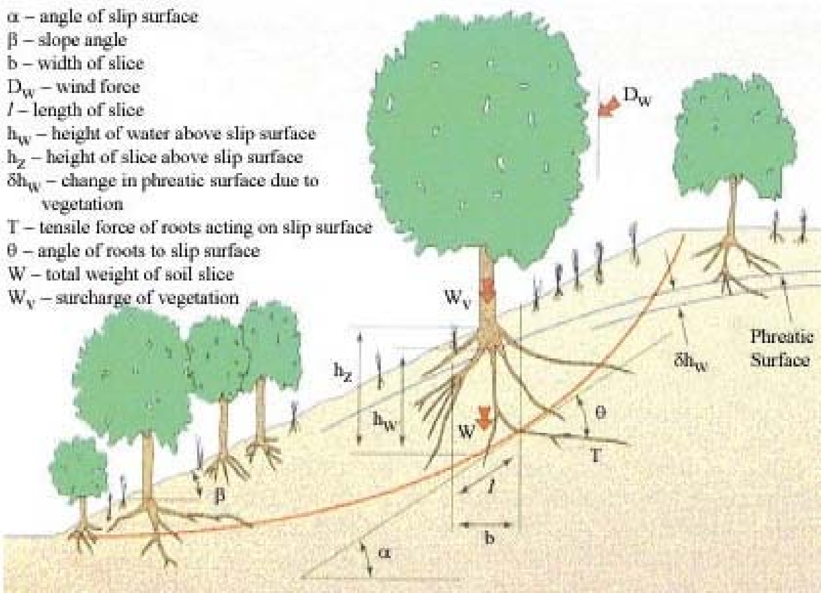

Figure 1. The effects of vegetation on a soil slope (Greenwood *et al*., 2004).

- additional effective cohesion due to the vegetation (c'_v)
- increase in weight of slice due to the vegetation (W_v)
- tensile reinforcement force by the roots present on the base of each slice (T)
- wind force (D_w)
- changes in undrained soil strength due to moisture removal by the vegetation (c_u)
- changes in pore water pressure (u_v).

These engineering influences can be used as input parameters in routine limit equilibrium slope stability analysis. The six influences that the vegetation has on a soil slope are further explained and methods of characterising and monitoring each one are discussed.

Effective cohesion, c'_v

Although the concept of effective cohesion in soils is much debated with some researchers advocating that no true cohesion exists in clay soils (e.g. Schofield 1998), back analysis of slope failures generally indicates an operational effective shear strength. This effective shear strength is conveniently represented by a small cohesion intercept in the order of $c' = 1$ to 2 kN/m^2. The value adopted within the stability analysis can have considerable influence on the calculated factor of safety, F (Greenwood 2006).

The reliable benefit of an enhanced c′ value is limited to shallow depths as root distribution is mainly concentrated within 1 m of the ground surface. The use of c′ values enhanced by c'_v would therefore be appropriate for grass and shrub areas where fine root distribution with depth is consistent and easily defined. The fine root network acts in a similar way to geosynthetic mesh elements by providing an apparent enhanced cohesion that increase the strength properties of the soil (Greenwood *et al*. 2004). (Note: The larger tap and lateral roots of deciduous and coniferous trees provide the tensile reinforcement force elements within the analysis).

Researchers have attempted to directly measure c'_v by designing and developing in situ shear apparatuses for this purpose (e.g. Norris & Greenwood 2003a; O'Loughlin & Ziemer 1982; van Beek *et al*. 2005). From experience, field shear tests tend to give an indicative undrained strength increase due to the presence of fine roots but overestimate the calculated factor of safety. It is essential for clay soils that the true effective parameters are thus obtained by back analysis or more sophisticated effective stress laboratory testing.

Root density and vertical root model equations have been developed to determine the overall shear strength increase due to all roots (ΔS) (Gray & Barker 2004; Gray & Ohashi 1983; Wu, McKinnell & Swanston 1979). The increase in shear strength from the root-soil composite based on the vertical or perpendicular root model is:

$$\Delta S = t_R (\sin\theta + \cos\theta \tan\phi) \qquad [1]$$

where θ is the angle of shear distortion in the shear zone, ϕ is the angle of internal friction of the soil and t_R is the mobilised tensile stress of the roots per unit area of soil. For roots that break in tension, equation [1] can be approximated to:

$$\Delta S = 1.2T_R(A_R/A) \qquad [2]$$

where T_R is the mean tensile strength of the roots and A_R/A is the cross-section of soil occupied by the roots (Wu *et al*. 1979), i.e. the predicted shear strength increase depends entirely on the mean tensile strength of the roots and the root area ratio.

Table 2 provides values of c'_v for a variety of vegetation types. The values are based on direct in situ shear tests, back analysis or from root density and vertical root model equations. Values vary from 1–25 kN/m^2 depending on type of soil and vegetation.

Mass of Vegetation, Wv

Vegetation may exert a surcharge on to the slope which could affect the stability. In urban environments, where there is a need to manage vegetation more rigorously, for example in preventing wind blown trees affecting transport networks, the effect of surcharge by vegetation is generally negligible. Only in well stocked forests, where trees are greater than 30 m in height and the total mass is in the order of 2 kN/m^2 can problems arise through excessive loading (Coppin & Richards 1990).

Vegetation (trees) can however prevent or promote slope stability depending on their location along a potential slip surface. Trees located at the toe of a potential landslip could add 10% to the factor of safety, or if located at the top reduce the factor of safety by 10% (Coppin & Richards 1990; Perry, Pedley & Reid 2003). It is important therefore that each situation must be individually assessed for the mass of vegetation involved. Plant evapotranspiration will reduce the weight of soil as moisture is lost. This can be important on slopes of marginal stability.

When vegetation on a large-scale is cleared from an area of a slope, there is a gradual reduction in soil strength due to the loss of evapotranspiration effects and root decay over time (O'Loughlin & Ziemer 1982; Payne 2003; Schmidt *et al*. 2001; Ziemer 1981). Studies have shown that the majority of the original reinforcement is lost in 4–15 years following clearance (Ziemer 1981). The timing of landsliding may not always be coincident with maximum root deterioration because of the low frequency of occurrence of required storm thresholds (Sidle *et al*. 1985). Failure does not normally occur immediately after felling but typically takes a few years to occur as the stability gradually decreases as soil moisture deficits are lost, and roots decay and lose strength (Hoskins and Rice 1992).

The removal of vegetation may also result in a reduction in applied loading which could create temporary suctions in clay soils. Soil softening may occur as available water is drawn in to satisfy the suction forces. This is of course akin to the recognised softening of overconsolidated clays due to relaxation of overburden pressures when placed in the top layers of an embankment from deep cutting (Greenwood, Holt & Herrick 1985).

The mass of the vegetation may be determined ideally by weighing complete trees where it is practical to do so, estimated from published in situ densities of wood (Savill 1991) or from published literature on typical weights/biomass of trees (e.g. Cannell 1982).

Table 2. Values of c'_v for grasses, shrubs and trees as determined by field, laboratory tests, and mathematical models.

Source	Vegetation, soil type and location	Root cohesion c'_v (kN/m^2)
Grass and Shrubs		
Wu‡ (1984)	Sphagnum moss (*Sphagnum cymbifolium*), Alaska, USA	3.5 – 7.0
Barker in Hewlett *et al.* † (1987)	Boulder clay fill (dam embankment) under grass in concrete block reinforced cellular spillways, Jackhouse Reservoir, UK	3.0 – 5.0
Buchanan & Savigny * (1990)	Understorey vegetation (*Alnus*, *Tsuga*, *Carex*, *Polystichum*), glacial till soils, Washington, USA	1.6 – 2.1
Gray § (1995)	Reed fiber (*Phragmites communis*) in uniform sands, laboratory	40.7
Tobias † (1995)	*Alopecurus geniculatus*, forage meadow, Zurich, Switzerland	9.0
Tobias† (1995)	*Agrostis stolonifera*, forage meadow, Zurich, Switzerland	4.8 – 5.2
Tobias† (1995)	Mixed pioneer grasses (*Festuca pratensis*, *Festuca rubra*, *Poa pratensis*), alpine, Reschenpass, Switzerland	13.4
Tobias† (1995)	*Poa pratensis* (monoculture), Switzerland	7.5
Tobias† (1995)	Mixed grasses (*Lolium multiflorum*, *Agrostis stolonifera*, *Poa annua*), forage meadow, Zurich, Switzerland	-0.6 – 2.9
Cazzuffi *et al.* § (2006)	Elygrass (*Elytrigia elongata*), Eragrass (*Eragrostis curvala*), Pangrass (*Panicum virgatum*), Vetiver (*Vetiveria zizanioides*), clayey-sandy soil of Plio-Pleistocene age, Altomonto, S. Italy	10.0, 2.0, 4.0, 15.0
Norris† (2005b)	Mixed grasses on London Clay embankment, M25, England	~10.0
van Beek *et al.* † (2005)	Natural understory vegetation (*Ulex parviflorus*, *Crataegus monogyna*, *Brachypodium* var.) on hill slopes, Almudaina, Spain	0.5 – 6.3
van Beek *et al.* † (2005)	*Vetiveria zizanoides*, terraced hill slope, Almudaina, Spain	7.5
Deciduous and Coniferous trees		
Endo & Tsuruta † (1969)	Silt loam soils under alder (*Alnus*), nursery, Japan	2.0 – 12.0
O'Loughlin & Ziemer † (1982)	Beech (*Fagus* sp.), forest-soil, New Zealand	6.6
Riestenberg & Sovonick-Dunford * (1983)	Bouldery, silty clay colluvium under sugar maple (*Acer saccharum*) forest, Ohio, USA	5.7
Schmidt *et al.* ‡ (2001)	Industrial deciduous forest, colluvial soil (sandy loam), Oregon, USA	6.8 – 23.2
Swanston* (1970)	Mountain till soils under hemlock (*Tsuga mertensiana*) and spruce (*Picea sitchensis*), Alaska, USA	3.4 – 4.4
O'Loughlin* (1974)	Mountain till soils under conifers (*Pseudotsuga menziesii*), British Columbia, Canada	1.0 – 3.0
Ziemer & Swanston ‡§ (1977)	Sitka spruce (*Picea sitchensis*) - western hemlock (*Tsuga heterophylla*), Alaska, USA	3.5 – 6.0
Burroughs & Thomas* (1977)	Mountain and hill soils under coastal Douglas-fir and Rocky Mountain Douglas-fir (*Pseudotsuga menziesii*), West Oregon and Idaho, USA	3.0 – 17.5
Wu *et al.* ‡ (1979)	Mountain till soils under cedar (*Thuja plicata*), hemlock (*Tsuga mertensiana*) and spruce (*Picea sitchensis*), Alaska, USA	5.9
Ziemer † (1981)	Lodgepole pine (*Pinus contorta*), coastal sands, California, USA	3.0 – 21.0
Waldron & Dakessian*(1981)	Yellow pine (*Pinus ponderosa*) seedlings grown in small containers of clay loam.	5.0
Gray & Megahan‡ (1981)	Sandy loam soils under Ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*) and Engelmann spruce (*Picea engelmannii*), Idaho,USA	~ 10.3
O'Loughlin *et al.* † (1982)	Shallow stony loam till soils under mixed evergreen forests, New Zealand	3.3
Waldron *et al.* † (1983)	Yellow pine (*Pinus ponderosa*) (54 months), laboratory	3.7 – 6.4
Wu ‡ (1984)	Hemlock (*Tsuga* sp.), Sitka spruce (*Picea sitchensis*) and yellow cedar (*Thuja occidentalis*), Alaska, USA	5.6 – 12.6
Abe & Iwamoto † (1986)	*Cryptomeria japonica* (sugi) on loamy sand (Kanto loam), Ibaraki Prefecture, Japan	1.0 – 5.0
Buchanan & Savigny * (1990)	Hemlock (*Tsuga* sp.), Douglas fir (*Pseudotsuga*), cedar (*Thuja*), glacial till soils, Washington, USA	2.5 – 3.0
Gray § (1995)	*Pinus contorta* on coastal sand	2.3
Schmidt *et al.* ‡ (2001)	Natural coniferous forest, colluvial soil (sandy loam), Oregon	25.6 – 94.3
van Beek *et al.* † (2005)	*Pinus halepensis*, hill slopes, Almudaina, Spain	-0.4 – 18.2

* Back analysis and root density information. † In situ direct shear tests. ‡ Root density information and vertical root model equations. § Laboratory shear tests.

Tensile root strength contribution, T

The depth and radial extent of roots (see Stone & Kalisz (1991) for ranges) is encouraging for the tensile strength of roots to be represented as anchors within the stability analyses calculations. The strength of a root can be measured in both the laboratory and in situ. In the laboratory, Instrom universal tensile testing machines are regularly used to measure the tensile strength of excavated fresh, dried and rehydrated roots. The tensile strengths of roots of various diameters from different species are typically in the order of 5–60 MPa (Table 3). Care must be taken when using Table 3, as the methodology employed differs between authors, root diameter is also not given and is an important factor when considering root strength (Stokes 2002).

Root tensile strengths generally show low strength values with large root diameters and high strengths with small root diameters. A decrease in root diameter from 5 to 2 mm can result in a doubling or even tripling of tensile strength (Gray & Barker 2004). Root strength is very much dependent on the biological components of the root e.g. smaller diameter roots possess more cellulose than larger diameter roots (Commandeur & Pyles 1991; Genet *et al*. 2005; Turmanina 1965).

Roots must have sufficient embedment and adhesion with the soil to make use of their available tensile strength to enhance slope stability. The biological growth patterns and interaction between the root and soil are complex but for engineering purposes the available force contribution from the roots may be measured by in situ pull out tests. Various apparatus have been designed to pull roots out of the ground, from simple hand pull to hydraulic jack systems (e.g. Norris & Greenwood 2003a; Operstein & Frydman 2000). Root pull out resistances are also included in Table 3 for a limited number of species.

The maximum breaking strength or pull out resistance of the roots together with an assessment of the root size and distribution (root area ratio) is used to determine the appropriate root reinforcement values for inclusion in the stability analysis (Greenwood *et al* 2004). When the laboratory derived root tensile strength and root pull out resistance (maximum breaking force) are compared, the root pull out resistance is significantly lower than the actual tensile strength of the roots. Experience in the field confirms this as the pull-out strength was generally within 50-70% of the tensile strength (at the clamp point) (Norris 2005b).

Wind loading, D_w

In urban environments, the influence of the wind on a soil slope would be insignificant as most urban centres are protected from the effects of wind by the presence of buildings. Only in extreme cases, would wind loading present a problem. The stability of individual trees on a slope are generally more vulnerable than forest stands or copses where the trees in the centre are protected and sheltered by those at the edge. In general, in slope stability analysis the forces exerted by the wind on the vegetation represent a much smaller proportion of the potential disturbing forces.

Wind loading on a forested slope can be calculated from equation [3] (Hsi & Nath 1970):

$$p = 0.5\ \rho_a V^2 C_D \qquad [3]$$

where p is wind pressure, ρ_a is air density (kg/m^3), V is wind velocity (m/s) and C_D is a dimensionless drag coefficient. Greenway (1987) suggested that a 90 km/hour wind, at an air density of 1.22 kg/m^3 and a drag coefficient of 0.2 would have a wind loading of approximately 1 kPa at the edge of the forest.

Soil strength increase due to moisture removal by roots

Moisture deficits around trees due to the effects of evapotranspiration and the search for water in drought conditions is well documented due to the large number of house insurance claims for compensation for structural damage (Biddle 1998; Hunt, Dyer & Driscoll 1999). However reliance on tree and shrub roots to remove water on embankments/cuttings and hence strengthen the soil is not so straightforward.

The CIRIA sponsored bioengineering trial at Longham Wood Cutting (M20) showed that the vegetation of grasses, herbs-forbs, and willow-alder shrubs had very little effect in increasing soil strength due to moisture removal by roots. This was as a result of the large seasonal variations in the moisture content (and hence the undrained soil strength). Plots with and without vegetation showed similar large seasonal variations (Greenwood *et al*. 2001).

The change in soil moisture content due to the vegetation can be monitored by vibrating wire piezometers, Time Domain Reflectometry (TDR) and Theta probe technologies. These are non destructive approaches to collecting moisture content data. Destructive approaches involve regular soil sampling by hand augering and determining gravimetric moisture content profiles with depth.

Table 3. Mean tensile root strength and root pull out resistance of shrub and tree species found in the United Kingdom.

Author	Species	Common Name	Tensile root strength (MPa)	Root pull out resistance (MPa)
Schiechtl (1980)	*Castanopsis chrysophylla*	Golden chinkapin	18	
Schiechtl (1980)	*Ceanothus velutinus*	Ceanothus	21	
Norris (2005a)	*Crataegus monogyna*	Hawthorn		8
Schiechtl (1980)	*Cytisus scoparius*	Scotch broom	32	
Schiechtl (1980)	*Vaccinium* spp.	Huckleberry	16	
Schiechtl (1980)	*Picea abies*	European spruce	28	
Coppin and Richards (1990); Schiechtl (1980); Coutts (1983); Lewis (1985)	*Picea sitchensis*	Sitka spruce	23; 16; 35; 40	
Lindström and Rune (1999)	*Pinus sylvestris*	Scots pine	7 (paper pots) 20 (nat.regen.*)	
Clark (2002)	*Acer pseudoplatanus*	Sycamore		2
Schiechtl (1980)	*Alnus firma* var. *multinervis*	Alder	52	
Greenwood et al. (2001)	*Alnus glutinosa*	Common alder		7
Schiechtl (1980)	*Alnus incana*	Grey alder	32	
Schiechtl (1980)	*Betula pendula*	Silver birch	37	
Riedl (1937)	*Betula verrucosa*	Silver birch	38	
Stokes & Mattheck (1996)	*Fagus sylvatica*	Common beech	55	
Riedl (1937)	*Fraxinus excelsior*	Ash	26	
Schiechtl (1980)	*Nothofagus fusca*	Red beech	36	
O'Loughlin and Watson (1979)	*Nothofagus sp.*	Southern beech	31	
Schiechtl (1980)	*Populus deltoides*	Poplar	37	
Coppin and Richards (1990)	*Populus nigra*	Black poplar	5 - 12	
Hathaway and Penny (1975)	*Populus yunnanensis*	Poplar	41	
Riedl (1937)	*Quercus pedunculata*	English oak	45	
Norris & Greenwood (2003b)	*Quercus pubescens*	Downy oak		7
Schiechtl (1980)	*Quercus robur*	English oak	32	
Turmanina (1965)	*Quercus rubra*	Red oak	32	
Norris (2005a)	*Quercus* sp.	Oak		7
Coppin and Richards (1990)	*Robinia pseudoacacia*	False acacia	68	
Coppin and Richards (1990)	*Salix cinerea*	Grey willow	11	
Schiechtl (1980)	*Salix fragilis*	Crack willow	18	
Schiechtl (1980)	*Salix helvetica*	Willow	14	
Schiechtl (1980)	*Salix matsudana*[1]	Contorted willow	36	
Schiechtl (1980)	*Salix purpurea*	Purple willow	36	
Norris (2005b)	*Sambucus nigra*	Elder	28	
Schiechtl (1980)	*Tilia cordata*	Small leafed lime	26	
Riedl (1937)	*Tilia parvifolia*	Lime	21	

*nat. regen. – natural regeneration.

Suctions and changes in pore water pressure due to vegetation (u_v)

Moisture content and soil water pressures are inherently related and can be monitored using a number of techniques:

- Standpipes are useful for indicating broad changes in water table levels on a seasonal basis but are not sophisticated enough to monitor the effects of growing vegetation (Greenwood *et al*. 2001).
- Tensiometers have been successfully used to record the detailed response of ground suctions to rainfall events and periods of wet or dry weather (Vickers & Morgan 1999).

There is a need for further research to develop a better understanding of the influence of the vegetation on the soil suction/moisture regime in slopes (Ridley *et al*. 2003).

STABILITY ANALYSIS TO INCLUDE THE INFLUENCES OF VEGETATION

The influences of vegetation on the factor of safety of a slope can be assessed by routine limit equilibrium stability analysis using the method of slices. One appropriate method to use is the Greenwood General equation (equation [4]) (Greenwood 1989; Morrison & Greenwood 1989). This method takes full account of hydrological (seepage) forces to give a realistic estimate of the factor of safety for all types of slopes and slip surfaces (Greenwood 2006).

$$F = \frac{\sum\left[c'\ell + \left(W\cos\propto - u\ell - \left(U_2 - U_1\right)\sin\propto\right)\tan\phi'\right]}{\sum W\sin\propto} \quad [4]$$

where c′ is effective cohesion at base of slice, *l* is length along base of slice, W is weight of soil, α is the inclination of base of slice to horizontal, ϕ′ is effective angle of friction at base of slice, *u* is water pressure on base of slice, U_1 and U_2 are interslice water forces on left and right hand side of slice (based on assumed hydrostatic conditions below the phreatic surface or derived from a flow net for more complex hydraulic situations).

The Greenwood General equation can be adapted to include the influences of the vegetation by the addition of the vegetation terms to the respective terms in equation 4 (Greenwood 2006). This gives equation [5],

$$F = \frac{\sum\left[(c'+c'_V)\ell + \left((W+W_V)\cos\propto - (u+\Delta u_V)\ell - \left((U_2+\Delta U_{2V}) - (U_1+\Delta U_{1V})\right)\sin\propto - D_W\sin(\alpha-\beta) + T\sin\theta\right)\tan\phi'\right]}{\sum[(W+W_V)\sin\propto + D_W\cos(\alpha-\beta) - T\cos\theta]} \quad [5]$$

where the additional parameters due to the vegetation are defined as: c'_v is enhanced cohesion due to the roots, W_v is weight of vegetation, Δu_v is the change in water pressure due to vegetation, $\Delta U1_v$ and $\Delta U2_v$ are changes in interslice water forces due to vegetation, D_w is wind force, T is tensile force of roots and θ is the angle of roots to slip surface.

An EXCEL spreadsheet, SLIP4EX, developed by the authors (Greenwood 2006) compares Greenwood's (Simple and General), Fellenius's, Bishop's and Janbu's methods of analysis for a given slip surface and quantifies the changes to the factor of safety due to the influences of the vegetation using Greenwood's and Fellenius's equations only.

Case studies of slopes in London Clay

An estimate of the contribution of the roots to the safety of soil slopes is given in Table 4 for two case studies of slopes in London Clay. The two London Clay slopes were situated on the M25 at Passingford Bridge (motorway embankment) and the M11 at Loughton, Essex (motorway cutting). For each case study, two conditions representing the age of the vegetation are given. In the analysis, it is assumed that the water table is at the ground surface; a limited number of roots cross the potential slip plane at a given depth; a partial factor of safety of 8 is applied to the root strength due to the uncertainties in the assumed or observed root distribution with depth and the availability of adequate root adhesion; and the roots intersect the slip plane at an angle θ of 45°. From Table 4, it can be seen that the addition of roots to the slope can significantly increase the factor of safety (up to 20%), with a further increase as the vegetation matures.

Table 4. Effects of the presence of roots on the factor of safety of a slope as modelled using SLIP4EX.

Parameters	**Case Study**			
	1. M25 embankment		**2. M11 cutting**	
	Immature vegetation	**Mature vegetation**	**Immature vegetation**	**Mature vegetation**
Slope angle	26º	26º	20º	20º
c´ (kN/m^2)	7	7	5	5
ϕ´ (º)	20	20	20	20
γ (kN/m^3)	19	19	19	19
Depth of slip surface (m)	1.5	1.5	1.5	1.5
Effective cohesion due to roots c'_v (kN/m^2)	2	3	2	3
Typical ultimate root strength (MPa)*	6	8.3	6	8.3
Typical root diameter (mm)	0.010	0.012	0.010	0.012
Typical no. roots per sq. m	2	4	2	4
Root force on slice T kN	0.79	3.13	4.81	19.17
F (no roots)	**0.88**	**0.88**	**1.01**	**1.01**
F (with roots)	**1.07**	**1.20**	**1.26**	**1.44**

* based on pull out resistance of hawthorn roots (Norris 2005a).

SLOPE DECISION SUPPORT SYSTEM

A decision support system was developed, during the ECO-SLOPES project, to assist expert and non-expert users in the evaluation and selection of soil bioengineering techniques and eco-engineering strategies for the protection of sloping ground from soil erosion and mass movements (Stokes, Mickovski & Thomas 2004; Mickovski & van Beek 2006). The new computer based system is known as a slope decision support system (SDSS). Decision support systems developed through the need for intelligent systems to assist in problem-solving and decision making (Carlsson & Turban 2001).

The SDSS is based on knowledge and experience of practising researchers and bioengineers. The knowledge behind the system is input as a series of hierarchical frames and output as rules to the user. The design and current software for the slope decision support system is based on a knowledge based system for foundation design called ConFound© (Toll & Barr 2001). The host software package provides both an environment in which knowledge can be entered by the expert (supervisor mode) and one in which this information can be explored interactively by the user (normal mode).

The user of the SDSS inputs as many generic details as possible regarding their specific project and site. Information such as ground conditions, nature of the slope, condition of the vegetation, land use activity and climate is input by manoeuvring through the hierarchal system of factors (Figure 2). Each factor has subsections which are activated by tick boxes (in the centre of Figure 2) and suitable selections chosen from the dropdown menus (on the right hand side of Figure 2). This input data is known as project specific information and is stored in a data file.

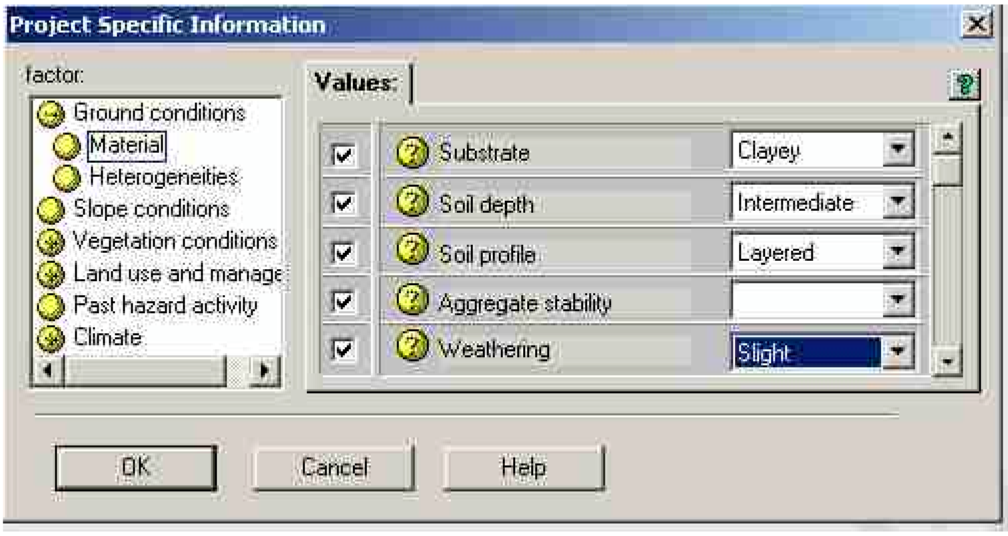

Figure 2. Entering the Project Specific Information. The user is prompted to enter all known factors relating to a particular sloping site. The more detailed the information entered, the more rigorous the hazard assessment will be and the more specific the eco-engineering methods proposed (Stokes *et al*. 2004).

The project specific information is internally matched to the knowledge base by rules. The rules reflect the level of information that is included in the knowledge base. The user on finishing inputting their data can then access the knowledge base. The output is a series of comments and or recommendations which the user can then apply to their particular site (Figure 3). Each comment has a confidence limit attached to it. The confidence limit serves as an indication of the trustworthiness of the comments returned by the slope decision support system which is based on best practice or generally accepted knowledge. This information is the basis of the SDSS (i.e., its knowledge base) but its provenance and dependability remain hidden from the user. The output page may recommend or advise on suitable bio and eco-engineering strategies for mitigation of the stability or soil erosion problem. The SDSS is currently available on the ECO-SLOPES website (http://construction.ntu.ac.uk) for users to download and feedback on its applicability.

CONCLUSION

Vegetation should now be considered as a practical engineering material which can be monitored and tested succesfully. The possible contribution of the vegetation can be incorporated into routine site investigation and its suitability can be assessed using a slope decision support system (SDSS) prior to construction works. The availability of tensile strength data for a wide range of roots or grasses, woody shrubs and trees, along with data on the effective cohesion the roots add to the soil, is a valuable aid in modelling slope stability either by limit equilibrium or finite element analysis.

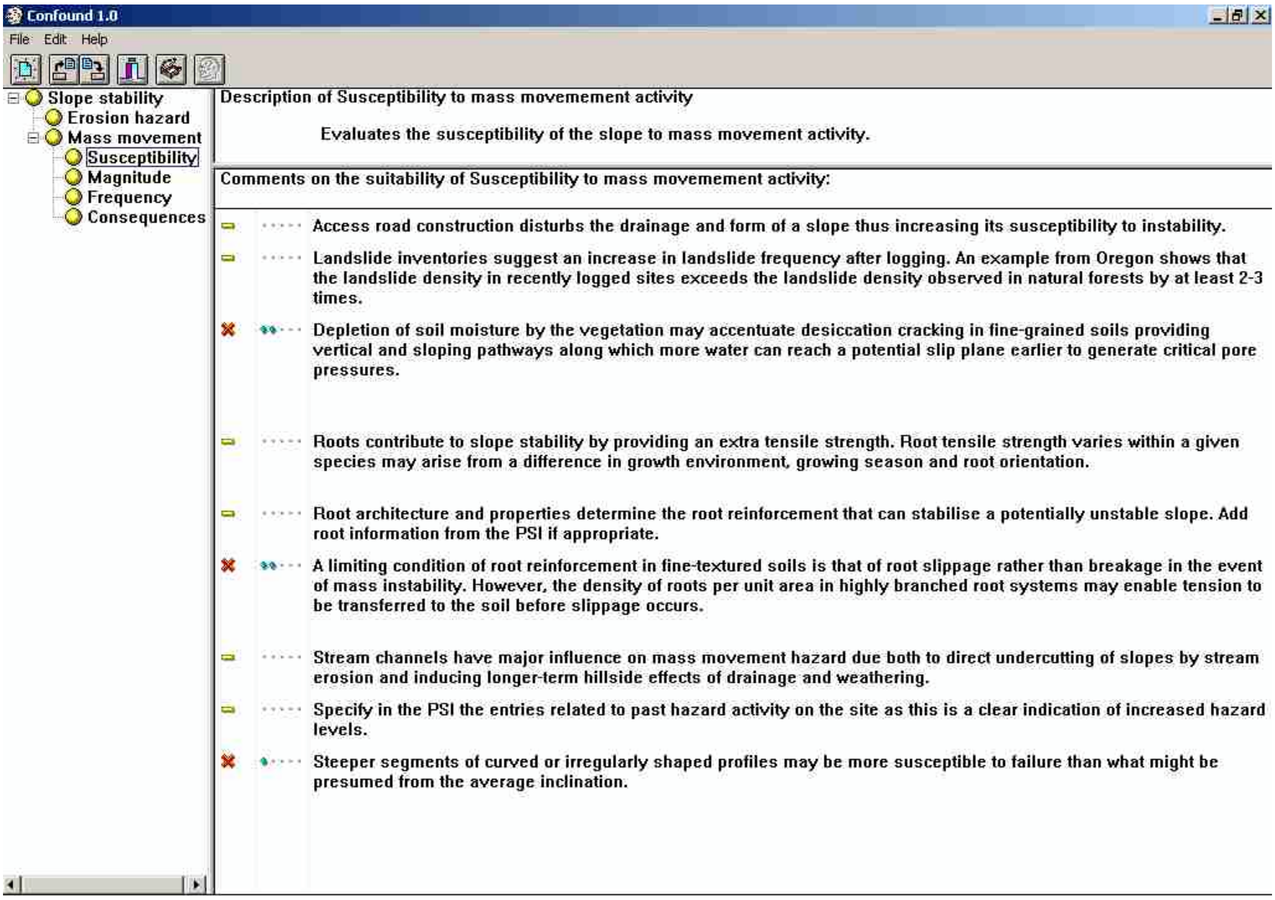

Figure 3. The European Slope Decision Support System. An example of the output advice and recommendations with associated suitability factor (ranges from highly unsuitable - highly suitable for example indicated by a red cross or yellow bar) and confidence levels (up to five blue marks).

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