Title: ASSESSING THE CONTRIBUTION OF VEGETATION TO SLOPE STABILITY

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Assessing the Contribution of Vegetation to Slope Stability

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Synopsis

Many embankments and cuttings associated with the transportation infrastructure in the UK are only marginally stable. Engineering techniques such as soil nailing, geosynthetic reinforcement, improved drainage and ground improvement by stabilisation are available to improve stability but the cost can be high. A lower cost solution may be to utilise vegetation, either self seeded or planted. The benefits and drawbacks associated with vegetation have been the subject of some debate.

The problems caused by vegetation in relation to building foundations are well documented and confirm that vegetation can have very significant influences on geotechnical parameters. Appropriate properly maintained vegetation can have the same significant influence to help provide additional stability to soil slopes.

This paper considers the potential engineering influences of vegetation and how it can be characterised on site within a geotechnical framework for stability assessments. The direct reinforcement available from the roots of trees and shrubs is identified as providing one of the most significant contributions to slope stability. Case studies in the UK, Greece and Italy demonstrate how results from in-situ root pull out tests may be used to estimate the potential reinforcement forces available from the roots. A scheme is presented to designate zones of influence within the soil according to the size and nature of the vegetation.

1. INTRODUCTION

Shallow slope instability is a common problem in embankments and cutting slopes particularly in the overconsolidated clay soils frequently encountered in the United Kingdom. The excavation and placement processes during earthworks result in a reduction in overburden stresses and the stiff overconsolidated clays are consequently susceptible to swelling and softening as they gain access to water. Zones of instability form typically at depths of 0.75 to 1.5 m below the slope surface (Perry,[1]; Greenwood,[2]). In the more sandy soils, and after placement of topsoil, erosion and washout can be a problem for newly constructed embankment and cutting slopes in the period before low vegetation (grass cover) becomes established (Perry,[3]).

Vegetation will generally establish itself naturally over time even on relatively barren soils, such as colliery spoil heaps, provided some nutrients, and water are available. In the United Kingdom most soil slopes will support an array of vegetation types. Grasses, shrubs and trees will initially self-seed as 'pioneer' vegetation and eventually evolve into a consistent pattern of coverage referred to as 'climax' vegetation.

Embankment and cutting slopes formed as part of the UK transportation infrastructure are generally seeded with grasses in accordance with the Specification for Highway Works (Design Manual for Roads and Bridges[4] and Manual of Contract Documents for Highway Works[5]) and selected shrubs and trees planted in accordance with locally agreed landscaping criteria. Whilst it is recognised that grass, once established, will prevent surface erosion, the vegetation is not intended for any purpose other than landscaping aesthetics.

It is becoming increasingly important, as the need for more eco-friendly solutions arises, for engineers to explore how vegetation might be selected and maintained to help enhance the soil strength and thereby reduce the risk of shallow slope failure.

When vegetation exists in the 'wrong' locations in relation to engineering constructions problems are frequently encountered (Fig. 1a). Poorly managed vegetation can cause problems due to amassing of fallen leaves and debris, blocking of drainage channels and the danger of windblown trees during storms affecting the safety of transportation operations. The detrimental effects on foundations located too close to certain trees leading to ground movements of a seasonal and permanent nature has been studied by the Building Research Establishment[6] and others e.g. Biddle,[7].

Vegetation can often be seen 'holding together' slopes that would otherwise degrade very rapidly (Fig. 1b). There is a general awareness and perception by engineers and the public that tree roots bind the soil together to resist ground erosion and movement. Perry[8] and Coppin[9] provide extensive information on the advantages and detrimental aspects of using vegetation for slope stabilisation.

This paper considers the potential engineering influences of vegetation and how it can be characterised on site within a geotechnical framework for slope stability assessments.

2. BACKGROUND

The publication by CIRIA of the book 'Use of Vegetation in Civil Engineering' (Coppin,[9]) formed a major landmark in introducing the concepts of enhancing soil properties with appropriate vegetation. This was followed up by a CIRIA sponsored field trial of specific vegetation on the M20 motorway at Longham Wood, near Maidstone, Kent (Greenwood,[10]).

The M20 trial set out to assess the relative importance of the influence of grass, shrubs and trees on the geotechnical parameters and stability of a 1 in 3 cutting slope in Gault Clay (Greenwood,[10]). The site, at Longham Wood, was monitored for a period of five years after which it was lost as the new Channel Tunnel Rail link was constructed immediately adjacent to the M20 passing through the trial site. During the final 'destructive' testing of the site, trenches were excavated to provide more detail of the ground and root growth conditions. Apparatus was developed to assess the in situ shear strength of the root reinforced Gault Clay and to determine the resistance of selected roots to pulling out of the ground (Greenwood,[10]; Norris,[11]). Moisture content changes during the trials were monitored by use of a neutron probe inserted down access tubes at specific locations (Vickers,[12]).

The M20 trial confirmed that

- willow and alder trees became established over the five year trial period and developed a substantial root network extending to 1.2 m depth.
- the instrumentation used, particularly that for determining soil water pressure, detected seasonal changes in the state of the slope and to some extent that produced by the root systems of the vegetation.
- seasonal changes in ground conditions were clearly indicated by the Mackintosh probe testing but this testing was not sensitive to the smaller changes due to the vegetation.
- the counterfort slope drains had no apparent effect on the vegetation or the soil and groundwater conditions in the upper 1.2 m of the slope.

- of the possible influences of the vegetation, the potential tensile root force appeared to be most effective in increasing the resistance to slope failure.

The report on the trial recommended that further monitoring be carried out on other sites to examine the effects of the vegetation in the medium - long term and to quantify the strength contribution available from different root systems (Greenwood,[10]).

The opportunity for further research was provided by the award of a £1.6m research grant under the European Community Fifth Framework Programme. This enabled Nottingham Trent University, as a partner in the ECOSLOPES project, to further develop the in situ shear and root pull out apparatus and to link the work done in the UK with related work in other European countries. The project is broad based with the partners focusing on the many related aspects of vegetation (current website www.ecoslopes.com). The final outcome of the project will be a reference data base and a guidance manual with a computer-aided decision support system to help the geotechnical engineer to select, specify and maintain appropriate vegetation to enhance slope stability in the various regions of Europe (Stokes,[13]; ECOSLOPES Manual,[14]).

3. THE INFLUENCES OF VEGETATION

The main influences of vegetation on the stability of a slope are shown in Fig. 2, developed from Coppin[9]. The parameters relating to the vegetation influences and the notation used for routine stability analysis by the method of slices are listed in Table 1. The parameters reflecting the effects of vegetation in stability analysis are:- an additional effective cohesion, an increase in weight of slice due to the vegetation, a tensile reinforcement force by the roots present on the base of each slice, windthrow force, possible changes in undrained soil strength due to moisture removal by the vegetation and changes in pore water pressure. These parameters are further explained and a description of the method of characterising each parameter within a geotechnical framework is discussed.

3.1 Enhanced cohesion, c'_v.

The concept of effective cohesion in soils has received considerable attention with some researchers advocating that no true cohesion exists in clay soils. However back analysis of slope failures has generally indicated an operational effective shear strength which is conveniently represented by a small cohesion intercept in the order of $c' = 1$ to $2\ kN/m^2$. The value adopted can have considerable influence on the calculated factor of safety, F.

The role of fine roots in resisting surface erosion is well documented (Morgan,[15]). Whilst fine roots are the major root components in garnering nutrients and moisture from the soil, their role in more general slope stability is less certain with perhaps a minor contribution as they help to maintain the integrity of the surface layers and prevent surface erosion. It would be expected that a fine root network would act to provide an apparent enhanced cohesion much in the same way that geosynthetic mesh elements have been demonstrated to enhance the soil strength properties (Andrawes,[16]). 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 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. Since accurate values of c' are difficult to measure, it is equally difficult to measure the additional contribution, c'_v, due to the vegetation. Values of c' and c'_v are often based on laboratory direct shear tests (Coppin,[9]). At Nottingham Trent University, ongoing development of an in situ shear apparatus (Norris,[11,17,18]; Greenwood,[10]) has enabled the additional contribution of the vegetation to be more accurately assessed. A description of the apparatus (Fig. 3) and test procedure is available in Norris[18]. Tests carried out on a motorway cutting in London Clay soil give an indication of enhanced cohesion as shown in Fig. 4.

Field shear tests tend to give an indicative undrained strength increase due to the presence of fine roots but, for clay soils, the true effective parameters are probably best obtained by back analysis or more sophisticated effective stress laboratory testing.

3.2 The Mass of Vegetation, W_v.

The mass of vegetation is only likely to have a major influence on slope stability when larger trees (dbh[*] of >0.3 m) are present. The loading due to a well stocked forest of 30 to 50 m tree height is in the order of 0.5 to 2 kN/m^2 (Coppin,[9]). A 30 m high tree having a dbh of approximately 0.8 m is likely to have a weight of 100-150 kN. Such trees located at the toe of a potential slip could add 10% to the factor of safety (Coppin,[9] Perry,[3]). Equally if located at the top of a potential slip the factor of safety could be reduced by 10%. Each situation must be individually assessed for the mass of vegetation involved. It should be borne in mind that plant evapotranspiration will reduce the weight of soil as moisture is lost. This can be important on slopes of marginal stability.

When larger trees are removed from the toe area of a slope, in addition to the gradual reduction in soil strength due to the loss of evapotranspiration effects, the reduction in applied loading could result in temporary suctions in clay soils which may lead to

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[*] dbh = standard measurement of trunk diameter taken at breast height (1.3 m). On slopes, dbh is measured from the upslope side of the tree.

softening 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,[2]).

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 (Table 2) or from published data sources on typical biomass of trees (e.g. Cannell,[19]).

3.3 Windthrow loading, D_w.

Windthrow loading is particularly relevant when considering the stability of individual trees but of lesser significance for general slope stability where the wind forces involved represent a much smaller proportion of the potential disturbing forces and trees within a cluster (stand) are sheltered to some extent by those at the edge.

Windthrow forces on single trees may be estimated from the method developed by Brown[20] and windthrow on forested slopes may be calculated by Hsi[21], both approaches are explained in Coppin[9].

3.4 Soil strength increase due to moisture removal by roots.

There have been various well documented observations of moisture deficit around trees (Biddle,[7]) due to the effects of evapotranspiration and the problems this has caused for buildings (Hunt,[22]). However reliance on tree and shrub roots to remove water on embankments/cuttings and hence strengthen the soil is not so straightforward.

Observations on the M20 at the Longham Wood trial site indicated large seasonal variation in the moisture content (and hence the undrained soil strength) of the south facing trial area. Plots with and without vegetation showed similar large seasonal variations. These variations masked and dominated any effects due to the vegetation over the five year period of the trial (Greenwood,[10]).

During particularly wet periods, the ability of the roots to influence the seasonal moisture content will be curtailed and therefore any enhanced soil strength gained previously by evapotranspiration will be reduced or lost entirely to an extent difficult to quantify. Hence this effect cannot be taken into account at such critical times. However, it can be assumed that there is a narrowing of the window of risk of failure due to soil saturation by storm events or periods of prolonged rainfall. Furthermore, whilst moisture content changes influence the undrained shear strength (c_u), the effective stress parameters ($c'$and ϕ') as generally used in routine stability analysis are not directly influenced by the changing moisture content, although the water pressures (suctions) used in the analysis will change.

It should be borne in mind that desiccation cracks, possibly extended during dry periods by the presence of certain vegetation, will encourage a deeper penetration of water and water pressures into the soil during wet periods. However, these cracks will subsequently be exploited by roots extending deeper into the soil as they follow pathways of least resistance.

The actual influence of the vegetation on moisture content can be monitored by Time Domain Reflectometry (TDR) and Theta probe technology. These are non destructive approaches to collecting moisture content data. The TDR is currently being trialled on a vegetated slope at Newbury, Berkshire (Clarke,[23]).

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

As discussed in the previous section, the moisture content and soil water pressures are related. On the M20, seasonal fluctuations in the water table, as measured by standpipes, were not significantly modified by the effects of the newly established vegetation. Tensiometers installed on the M20 project (Vickers,[12]) and on other slopes have proved much more worthwhile in recording the detailed response of the ground suctions to rainfall events and periods of wet or dry weather. Seasonal pore water pressures and moisture changes are currently being monitored on a lightly vegetated (grass/shrub cover) slope at Newbury, Berkshire (Clarke,[23]).

3.6 Tensile root strength contribution, T.

The tensile strengths of roots of various diameters from different species have been measured in the laboratory and found to be typically in the order of 5 - 60 MN/m^2 (Table 3) (Coppin,[9]). In the field, to make use of the available tensile strength to enhance slope stability the root must have sufficient embedment and adhesion with the soil. 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. Measurement of the root resistance to pull out has been carried out by various methods ranging from hand pull to screw and hydraulic jacks (e.g. Operstein,[24]; Norris,[18]). The pull out method depends very much on the size of root and the type of equipment and reaction frame available. A constant rate of strain is required, typically 1% per minute, and a means of measuring the resistance by spring balance or load cell at defined displacements. Procedures for the root pull out test are given in Norris[18] and Greenwood[25].

Design of the clamp to grip the root requires particular attention. Many species of root, particularly when fresh, demonstrate a tendency for the bark to separate and slide over the core wood during tensile testing. It is therefore often necessary to strip the bark at the clamp and to grip directly on to the core wood. In some cases, slipping of the clamp, may be overcome by wrapping a piece of sandpaper around the root to improve grip. The tensile strength is then calculated based on the diameter of the core wood assuming that the bark is making little contribution to the strength of the root. However it is the bark which is in contact with the soil and generating the adhesion resistance so the full root diameter must be considered in the pull out assessment (Greenwood,[25]).

Analysis of the pull out testing on the M11 motorway site has revealed different types of root failure, depending on root morphology and branching (Norris,[18]). Roots which have no branches tend to fail in tension and pull straight out of the ground with minimal resistance. Roots that have multiple branches, fail in stages as each branch breaks within the soil. These types of roots can be divided into two categories; those that break with increasing applied force and those that initially reach their maximum peak force then maintain a high force which gradually reduces as the root branches fail after considerable strain. In some tests, significant adhesion between a section of the root and the soil can be measured before the root finally slips out of the soil mass. Fig. 5 shows schematic examples of the types of failure observed during root pull out tests of Hawthorn roots.

The maximum breaking force 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 (further described below).

4. STABILITY ANALYSIS TO INCLUDE THE INFLUENCES OF VEGETATION

The influences of vegetation on the factor of safety of a slope are conveniently assessed by routine limit equilibrium stability analysis by the method of slices. Various methods of stability analysis are available. The Greenwood General equation (equation [1]) (Greenwood,[26]; Morrison,[27]) is considered appropriate because it 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.

$$F = \frac{\Sigma\left[c'\ell + \left(W\cos\propto - u\ell - \left(U_2 - U_1\right)\sin\propto\right)\tan\phi'\right]}{\Sigma W\sin\propto} \qquad [1]$$

The interslice water forces, U_1 and U_2, may be calculated based on assumed hydrostatic conditions below the phreatic surface or derived from a flow net for more complex hydraulic situations. It should be noted that if the interslice forces U_1 and U_2 are equal the equation becomes:-

$$F = \frac{\Sigma\left[c'\ell + \left(W\cos\propto - u\ell\right)\tan\phi'\right]}{\Sigma W\sin\propto} \qquad [2]$$

This equation [2] is the well known Swedish (Fellenius) equation which is appropriate to use for a planar, slab slide on a continuous slope with seepage parallel to the slope. However the user should be cautious as in practice the parallel seepage is often interrupted by less permeable layers resulting in a local reduction in the factor of safety.

The actual hydraulic conditions are therefore more correctly modelled using the General equation [1] (Morrison,[27]).

The mathematically 'simple' form of the Greenwood General equation and the factor of safety defined in terms of restoring and disturbing forces allows straightforward inclusion of the various vegetation influences (equation [3]).

$$F = \frac{\Sigma\left[(c'+c'_v)\ell + \left((W+W_v)\cos\propto -(u+\Delta u_v)\ell - \left((U_2+\Delta U_{2v})-(U_1+\Delta U_{1v})\right)\sin\propto -D_w\sin(\alpha-\beta)+T\sin\theta\right)\tan\phi'\right]}{\Sigma[(W+W_v)\sin\propto +D_w\cos(\alpha-\beta)-T\cos\theta]} \quad [3]$$

It is noted that in equation [3], the tangential component of the root reinforcement force, $T\cos\theta$, is correctly deducted from the denominator as it is a negative disturbing force. In practice the term is often assumed to be a positive restoring force and is added to the numerator. The differences in the calculated factor of safety by either approach are small with identical values calculated when F = 1.

Whilst the factor of safety in equation [3] is expressed as a traditional ratio of restoring to disturbing forces, the equation may be readily adapted to the inclusion of partial factors on each individual term in accordance with recommendations of more recent British Standards and European Codes of Practice.

An EXCEL spreadsheet, SLIP4EX, has been developed by the authors to compare the various routine methods of analysis for a given slip surface and to quantify the changes to the factor of safety due to the influences of the vegetation. A version, SLIP5EX, incorporating graphics and search routines for critical slip surfaces is being developed in association with University of Amsterdam (Van Beek,[28]).

4.1. ZONES OF INFLUENCE OF VEGETATION

The changed soil parameters due to the influence of the vegetation may be assessed by considering typical distributions of roots below a vegetated area. If the vegetation coverage is consistent over the area, enhanced parameter zones may be represented as zones parallel to the slope (Fig. 6). For isolated larger trees and shrubs a distribution such as that shown in Fig. 7 might be considered as being typical of the saucer-shaped root network frequently observed. The suggested approximations of zones of root influence need to be assessed for individual species in particular soil and growing conditions.

4.2 ESTIMATION OF AVAILABLE ROOT REINFORCEMENT FORCE

Observation and measurement in the field has indicated that the direct reinforcement forces available due to the presence of the roots are likely to be the main contribution of the vegetation to slope stability (Coppin,[9]; Greenwood,[10]).

In order to estimate the value of T, the available root force acting on the base of the slice of the analysis, for inclusion in the stability equation [3], the size and distribution, strength and pull out resistance of the roots must be considered together with an appropriate partial factor of safety to reflect the uncertainty in the assumptions made.

It is convenient to introduce the term T_{ru}, the ultimate root force per square metre across a given plane (for example the slip surface) within a particular soil zone. T_{ru} may be estimated based on the observed or assumed root distribution and determination of characteristic resisting forces for the roots of varying diameter by root pull out and tensile strength testing. Values of T_{ru} may be assigned for particular root zones as illustrated in Figs. 6 and 7.

The natural evolution of vegetation roots is such that they are generally just sufficient to serve their purpose of maintaining stability against gravitational and wind forces. It is observed that the pull out resistance of a root is likely to be only slightly less than the measured tensile strength of the root. In the absence of specific pull out data, the tensile strength of the root is therefore likely to be a reasonable indicator of the maximum pull out resistance available (Greenwood,[25]).

T_{ru} may therefore be estimated based on the measured pull out strengths or estimated as a proportion of the measured or assumed tensile strength of the roots crossing the soil plane.

T_{ru} = assigned ultimate root resistance (strength) x root area per square metre of soil [4]

The available (design) root force on that plane, T_{rd} per square metre of soil, is then derived by application of a suitable partial factor of safety, F_r .

i.e. $$T_{rd} = \frac{T_{ru}}{F_r} \qquad [5]$$

There is much uncertainty about the root distribution in the ground and the resisting forces which are available for a particular slip surface geometry and soil conditions. For this reason a high value of F_r is recommended. Values of F_r of around 8 or 10 are currently used to reflect the uncertainties and to allow for the large strains, typically in the order of 20%, necessary to generate the ultimate root resistance to pull out. It may be possible to reduce the factors of safety as the root zones around the vegetation are better characterised on a seasonal basis and more root pull out information becomes available.

The force T applicable to a slice of the stability analysis is given by equation [6].

$$\mathrm{T} = T_{rd}\ell \qquad [6]$$

Where ℓ = the length of slip surface affected by the roots (assuming unit width of slope).

The angle θ between the root direction and the slip surface is typically assumed to be 45°. The calculated factor of safety for the slope is not generally sensitive to the value of θ selected as the terms $T\cos\theta$ and $T\sin\theta \tan\phi'$ in the stability equation [3] tend to compensate each other as θ changes. The assumption of $\theta = 45°$ is conservative because, as shearing occurs and the roots distort, the value of θ is likely to decrease thereby slightly increasing the available root resisting forces on the slip surface.

4.3 EXAMPLES OF THE INFLUENCE OF VEGETATION

The following examples illustrate the application of this approach to cases studied.

4.3.1. *M20 trial – Longham Wood*

On the M20 site it was observed that the willow roots extended down to 1.2 m or more. At 1 m depth (the typical depth of a shallow slope failure in overconsolidated clay), there may be say 4 roots of 12.5 mm diameter crossing each square metre of the potential slip plane and acting in a direction likely to be beneficial to resisting downslope movement. The ultimate tensile ‘pull out’ strength of the roots measured by tests in the field was typically 8 MN/m^2 (based on the diameter at the clamp). By substituting these values into equations [4] and [5] and assuming F_r=8, T_{rd} is approximately equal to 0.5 kN per square metre of slip surface. Assuming, for simplicity, a continuous 1 in 3 slope, and soil parameters $c' = 1.5$ kN/m^2 and $\phi' = 23°$, the calculated factor of safety using equation [3] would increase from 0.90 without roots to 0.99 due to the effects of roots at 1 m depth (assuming $T_{rd} = 0.5$ kN/m^2 and $\theta = 45°$). This represents a significant 10% increase in the factor of safety. This calculation is indicative of the benefits of root reinforcement. Closer to the ground surface, say 0.5 m depth, the value of T_{rd} may increase to 1 kN and equally at lower levels, below 1.5 m, reduce to 0 (Norris,[11]).

4.3.2. *'ECOSLOPES' Greece and Italy examples*

An estimate of the contribution the roots might make to the safety of the slope is given in Table 4 for two case studies of a weathered metamorphic/sedimentary soil slope in Greece and a slope consisting of Tertiary marls, Molise sequence, in Italy (Norris,[29]). Again, it is assumed that 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 and θ is assumed to be 45°. The soil parameters and slope angles for each site are included in Table 4. The ultimate root strength and root diameters are based on root pull-out resistance results described in Norris[29]. It was assumed that roots are present at the depth of the slip surface with adequate bond length to generate the tensile strength. From Table 4, it can be seen that with the assumed presence of roots a significant increase (>10%) in the factor of safety can be achieved.

5. CONCLUSIONS

A framework has been established for assessing the contribution of vegetation to slope stability. Methods are available to consider the likely influences of vegetation including its mass, effects on the groundwater regime, enhanced cohesion due to fine roots, windthrow and the anchoring effects of the larger roots. Of these influences the tensile anchoring contribution of the larger roots is considered to be the most positive and reliable factor. Techniques for measuring root tensile forces have been discussed.

Incorporation of the available root forces into routine stability analysis has been demonstrated. At this stage relatively high partial factors of safety (say $F_r = 8$ or more) are recommended when determining the available root force from the measured values of the ultimate root pull out resistance. This allows for uncertainties and variability in the assumed or observed root distribution with depth and the availability of adequate root /soil adhesion throughout the seasons of the year. It also recognises that large strains are typically needed to generate the ultimate root pull out forces.

Further work is required to improve the understanding of the soil-root interaction and potential for further development and control of vegetation and its root systems to help assist slope stability. It is important that appropriate vegetation maintenance programmes are defined to accompany planting proposals. The engineer must be realistic in the expectations of what can be achieved from a natural, growing product subject to the vagaries of nature.

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Captions to Figures

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Figure 2. The influences of vegetation on slope stability (after Coppin,[9]).

Figure 3. In situ shear and root pull out apparatus developed at Nottingham Trent University (Norris,[18]).

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Captions to Tables

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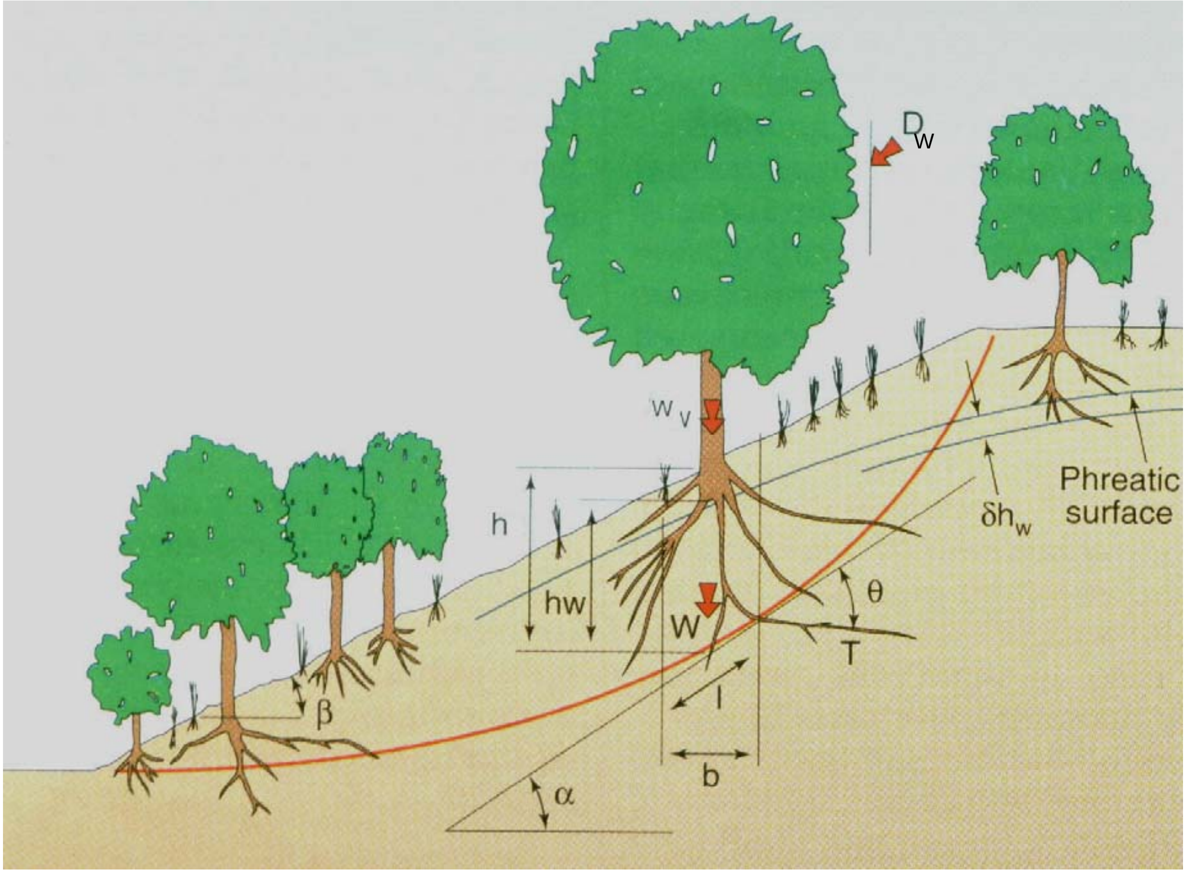

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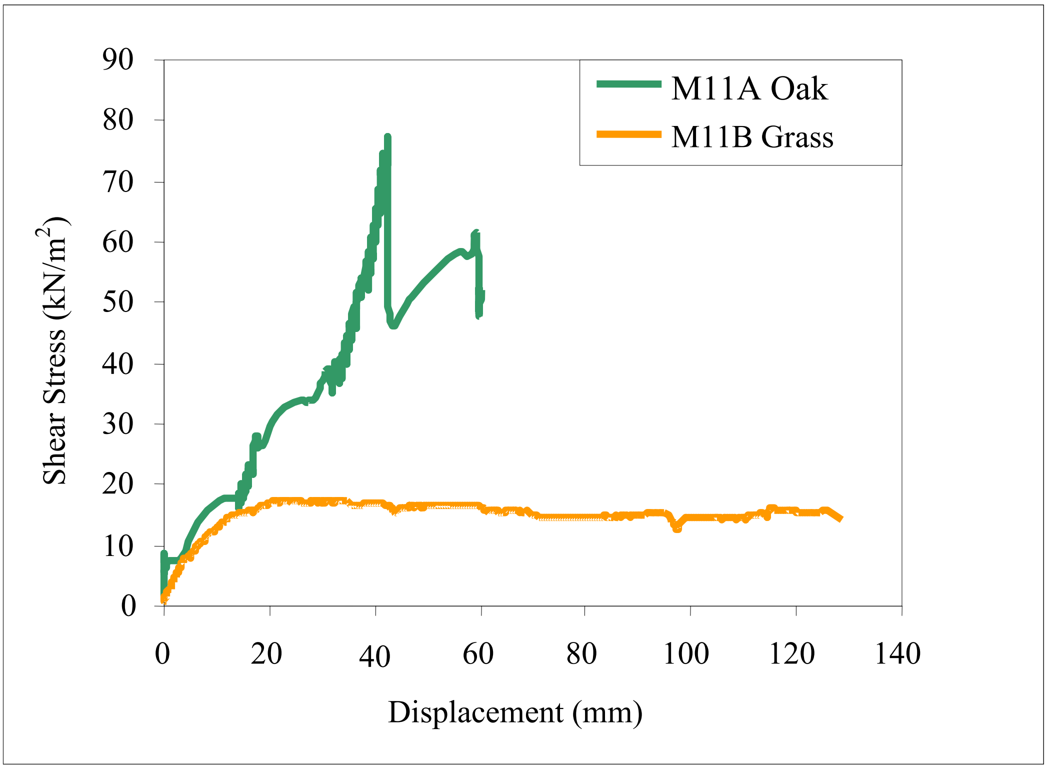

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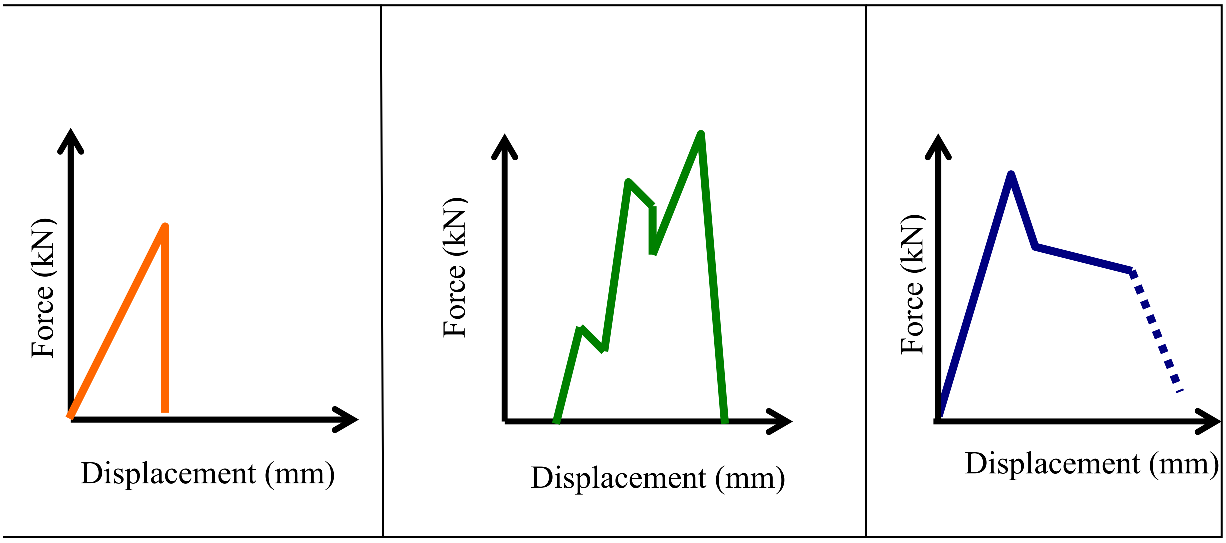
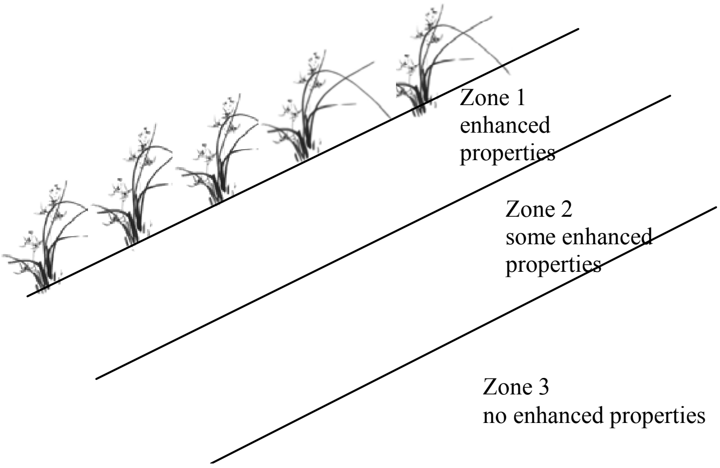


Single root with minimal root-soil interaction

Multibranched root with some root-soil interaction

Full root-soil interaction

Figure 6. Zones of enhanced soil properties for regular vegetation cover (Greenwood,[31]).



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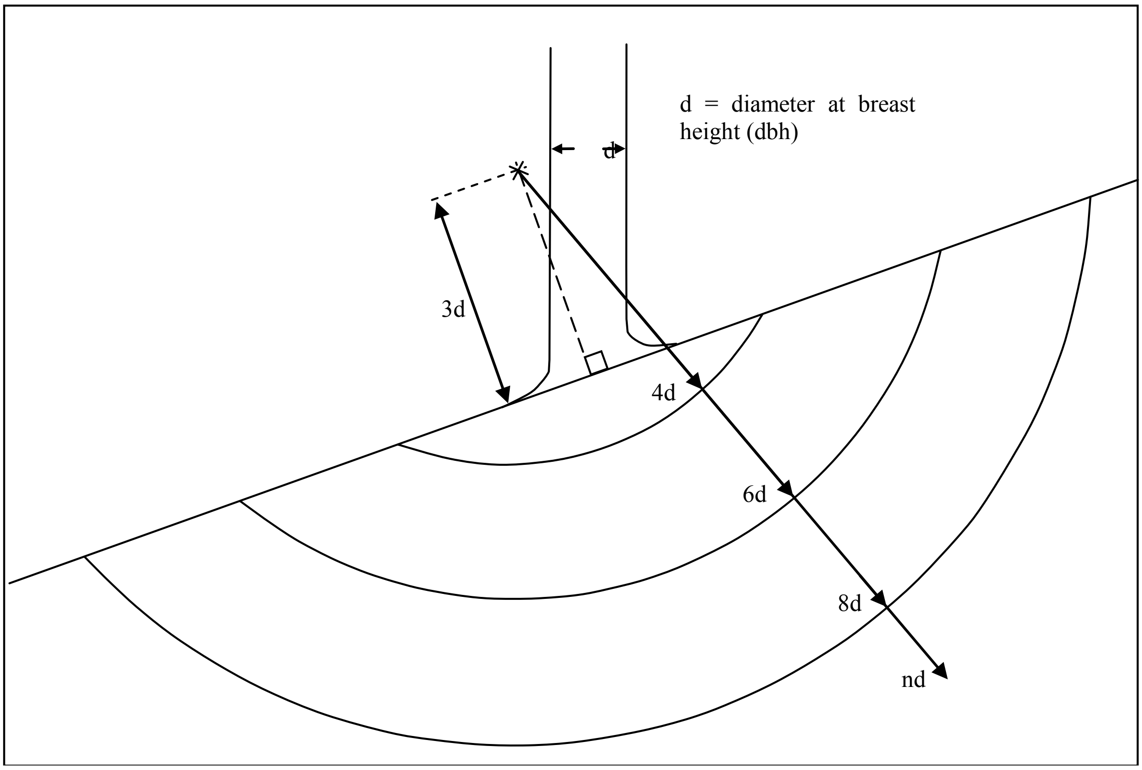

Table 1. Notation

Basic parameters and dimensions used in stability analysis by method of slices

Term	Units	Description
h	m	Average height of slice
b	m	Width of slice
ℓ	m	Length (chord) along base of slice
c'	kN/m^2	Effective cohesion at base of slice
ϕ'	degrees	Effective angle of friction at base of slice
γ	kN/m^3	Bulk Unit weight of soil in slice
γ_w	kN/m^3	Unit weight of water (usually taken as 10 kN/m^3)
W	kN	Total weight of soil in slice (for layered soils, 1,2,3 etc. $W = (\gamma_1 h_1+\gamma_2 h_2+\gamma_3 h_3+etc) \times b$)
α	degrees	Inclination of base of soil slice to horizontal (may be negative at toe)
h_{w1}	m	Height of free water surface at left hand side of slice
h_{w2}	m	Height of free water surface at right hand side of slice
U_1	kN	Water force on left hand side of slice (from flow net, seepage calculations or based on h_{w1})
U_2	kN	Water force on right hand side of slice (from flow net, seepage calculations or based on h_{w2})
h_w	m	Average piezometric head at the base of the slice. For hydrostatic $h_w = (h_{w1} + h_{w2})/2$
u	kN/m^2	Average water pressure on base of slice (= $\gamma_w \times h_w$)
F	ratio	Factor of Safety (usually shear strength/ shear force on slip plane)
F_m	ratio	Factor of Safety in terms of moment equilibrium
F_f	ratio	Factor of Safety in terms of horizontal force equilibrium

Vegetation, Reinforcement and Hydrological effects

c'_v	kN/m^2	Additional effective cohesion at base of slice (due to vegetation etc.)
W_v	kN	Increase in weight of slice due to vegetation (or surcharge)
T	kN	Tensile root or reinforcement force on base of slice
θ	degrees	Angle between direction of T and base of slip surface
D_w	kN	Windthrow force (downslope)
β	degrees	Angle between wind direction and horizontal (often assume equal to slope angle)
δh_{w1}	m	Increase in height of free water surface at left side of slice
δh_{w2}	m	Increase in height of free water surface at right side of slice
δU_1	kN	Increase in water force on left hand side of slice
δU_2	kN	Increase in water force on right hand side of slice
δh_w	m	Increase in average piezometric head at base of slice (due to vegetation)
δu_v	kN/m^2	Increase in average water pressure at the base of the slice, $= \gamma_w \times \delta h_w$
T_{rd}	kN/m^2	Available (design) root force per square metre of soil on a particular plane (for example the slip surface)
T_{ru}	kN/m^2	Ultimate root force per square metre of soil
F_r		Factor of Safety applied to ultimate root force to reflect the uncertainty in root distributions and assumptions made

Table 2. In situ density of common tree species on the UK's transport infrastructure (Savill,[30]).

Tree species	Density (Mg/m^3) at 15 % moisture content
Beech	0.720
Ash	0.710
Birch	0.670
Sycamore	0.630
Oak	0.720

Table 3. Tensile strength and pull out resistance of vegetation found on the UK's transport infrastructure.

Common name	Latin name	Tensile strength[1] (MN/m^2)	Pull out resistance[2] (MN/m^2)	Source of data
Common alder	*Alnus glutinosa*		7	Greenwood[10]
Alder	*Alnus incana*	32		Coppin[9]
Birch	*Betula pendula*	37		Coppin[9]
Broom	*Cytisus scoparius*	32		Coppin[9]
Elderberry	*Sambucus nigra*		0.1-2	Clark[32]
Hawthorn	*Crataegus monogyna*	16-159		Norris[33]
		0.6-21		Norris[34]
			2-25	Norris[35]
		7-90		Papa[36]
Black Poplar	*Populus nigra*	5-12		Coppin[9]
Hybrid Poplar	*Populus euramericana*	32-46		Coppin[9]
Oak	*Quercus robur*	32		Coppin[9]
Sycamore maple	*Acer pseudoplatanus*		2	Clark[32]
Willow	*Salix purpurea*	36		Coppin[9]
Sallow	*Salix cinerea*	11		Coppin[9]

1. Tensile strength for live roots as tested in the laboratory.
2. Pull out resistance as measured from in situ tests.

Table 4. Possible effects of the presence of roots on the Factor of Safety for two case studies in Greece and Italy (Norris,[29]).

Case Study	Slope angle, α	Soil parameters			Depth of slip surface m	Assumed water table (depth)	Typical ultimate root strength MN/m^2	Assumed available root strength = ult/8 MN/m^2	Typical root diam mm	Typical no. roots per sq.m	T_{rd} kN/m^2	F (no roots)	F (with roots)
		c′ kN/m^2	Φ′ °	γ kN/m^3									
1A. N. Greece	20°	0	35	18	0.5	Surface	12	12/8	8	6	0.45	0.71	0.89
1B. N. Greece	20°	0	35	18	0.5	Dry	12	12/8	8	6	0.45	1.92	2.25
2. Central Italy	27°	2.6	25	18	1.0	0.5 m	10	10/8	12	4	0.57	0.95	1.04