Chapter 5

HAZARD ASSESSMENT OF VEGETATED SLOPES

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Abstract: *The hazard assessment of vegetated slopes are reviewed and discussed in terms of the stability of the slope both with and without vegetation, soil erosion and the stability of the vegetated slope from windthrow and snow loading. Slope stability can be determined by using either limit equilibrium or finite element stability analysis methods. The limit equilibrium methods are extended to incorporate the vegetation parameters that are important for the stability of a vegetated slope. The factors that contribute to soil erosion are reviewed and the techniques for assessing and measuring the rate of soil erosion are presented. The assessment of windthrow hazards are comprehensively discussed and a mechanistic model called ForestGALES is introduced which has flexibility for testing many different forest management scenarios. The hazards presented by snow loading on forested slopes are briefly reviewed.*

Key words: hazard assessment, slope stability, soil erosion, vegetated slopes, windthrow.

1. INTRODUCTION

Hazards may be defined as sources of potential harm resulting from natural processes (natural hazards) or human activity (man-made hazards). The risk of a hazardous event occurring can be assessed in terms of the

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probability and possible impact of the event. In this chapter, a limited number of natural and man-made hazards and their determination is discussed, and related to various processes on slopes. The following hazards are elaborated in detail:

- Slope (in)stability (Sections 1.1 and 1.2)
- Soil erosion (Section 2)
- Stability of vegetation on slopes from windthrow and snow hazards (Section 3)

and general techniques to assess hazards, i.e.,

- Mapping inventory techniques, both in the field and using aerial photographs/remote sensing techniques
- Geographical Information Systems (GIS) techniques
- Numerical modelling
- Decision support systems

Before starting the actual assessment it is necessary to make some general remarks on the assessment related to slope characteristics, soil materials and vegetation.

Initially, a simple inventory should be carried out, focussing in particular on the presence of:

- Signs of mass wasting, slope angle and sudden slope breaks, susceptible geological and soil materials, adverse hydrological conditions and topographical surfaces, e.g., areas showing signs of mass wasting may include sudden slope breaks and materials with adverse soil mechanical properties, e.g., certain clay rich materials. Unfavourable hydraulic conditions may also exist, e.g., spring zones and badly drained areas.
- Erosion processes and vegetation damage from the past.

Areas showing signs of soil erosion may be indicated by partial or absent vegetation cover, truncated soil profiles, erodibility of soil material as well as land use practices and soils with impervious layers close to the surface.

Areas where *vegetation* is or has historically been known to be damaged by several processes, e.g., forest fires, storms, diseases or insect invasions, are also susceptible.

Artificial slopes need special attention (both existing and designed). Two main types can be distinguished:

1. *piled up materials*. Artifical slopes consisting of loosely piled materials often show a lack of cohesion and internal strength, making them very sensitive to slope failure or rill and gully erosion.
2. *consolidated materials*. Artificial slopes consisting of compacted and consolidated clays are prone to slope failure if design errors have been incurred, related to the over-steepening of slopes and tension release after cutting the slope.

Following the initial assessment, in which a Slope Decision Support System (Mickovski et al. 2005; Mickovski and van Beek 2006) might be of help, more detailed methods can be used which are discussed in the following sections.

Risk assessment of the hazards described here is only partly addressed in this chapter. For further description of this, the reader is referred to standard textbooks on hazard risk assessment (Glade et al. 2005).

1.1 Slope stability assessment

When assessing the stability of a slope, either vegetated or non vegetated, certain information is required on the topography, site layout, geology, soil and groundwater conditions that may be present or are likely to be encountered. Slopes generally fail on either geologically weak points in rock slopes or on shear planes in soil slopes. The conditions along a potential failure surface must, therefore, be defined in terms of:

- Normal stress acting on the failure surface
- Pore water pressure
- Shear strength of the material intersected by the failure surface
- Pull out forces generated by soil reinforcements or anchors.

The stability of slopes may conveniently be analysed by limit equilibrium methods, e.g., Duncan and Wright (2005). Limit equilibrium analysis requires information about the strength of the soil, but not its stress-strain behaviour. Slope movements are usually analysed by finite-element methods i.e., finite element software programs such as PLAXIS (http://www.plaxis.nl/). For these methods, characteristic stress-strain behaviour is required.

1.1.1 Slope stability analysis by limit equilibrium methods

In limit equilibrium techniques, e.g., Bishop (1955) and Fellenius (1936), the stability of a possible slip surface is assessed by comparing the gravitational disturbing forces with the available shearing resistance (shear strength) of the ground along the slip surface (Figure 5.1). For stability, disturbing forces acting along all potential slip planes must be less than the resisting forces that can be mobilised along them. The disturbing forces are due to the self weight of the material lying above the failure surface and to any external loads. Resisting forces are generated by the strength of the soil and by the pull out forces generated by soil reinforcement (for instance, the roots of vegetation). For stability to be maintained the available shear strength must exceed the disturbing forces.

The Factor of Safety (FOS) against failure is expressed by:

$$FOS = \frac{shear\ resistance}{shear\ force\ required\ for\ equilibrium} = \frac{restoring\ force}{disturbing\ force} \quad (1)$$

The FOS is generally expressed in terms of moment equilibrium, where the FOS for a stable slope will be greater or equal to 1.

For a circular slip surface, FOS is expressed in terms of moment equilibrium (FOS_m) with the lever arm (radius R) cancelling from the numerator and denominator of the equation.

For non-circular slip surfaces, FOS may be assumed to be expressed in terms of pseudo-moment equilibrium (with a changing value of R which is assumed to cancel from the numerator and denominator).

The FOS might also be expressed in terms of horizontal force equilibrium (FOS_f) for compatibility with retaining structure design.

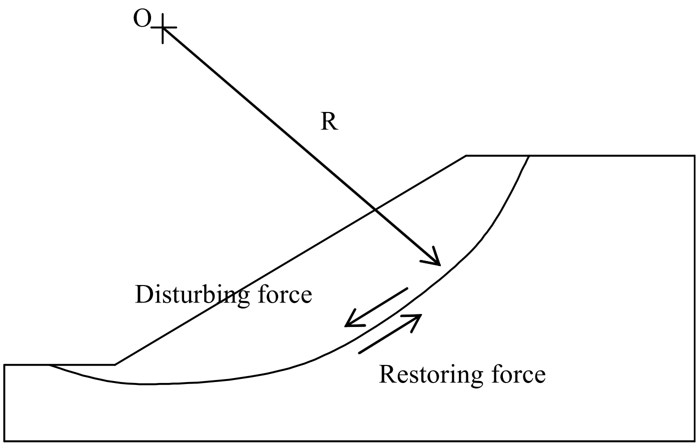


Figure 5-1. Forces acting on a circular slip plane. O is the centre of the slip circle, R is the radius of the slip circle or lever arm.

Method of Slices

The FOS for a slope is normally derived by the method of slices (Duncan and Wright 2005; Greenwood 2006). This method uses the friction block acting on an inclined plane as the basis for stability analysis. A block or slice of soil of unit width, above a potential slip surface, has the same friction principles applied to control stability but now there is the added effect of soil cohesion and water pressure which will govern the effective stresses.

To determine the FOS by the method of slices, a circular slip surface with radius R is assumed. The soil mass above the arc is divided into a number of vertical slices of width *b* and varying height *h* (Figure 5.2). The base of each slice is assumed to be a straight line inclined at an angle α to the horizontal and with a length *l* (Figure 5.2). The slope is divided into slices for analysis purposes only. It is assumed that all slices rotate around the centre of the circle O as a whole body. This implies that forces must act between the slices, termed interslice forces.

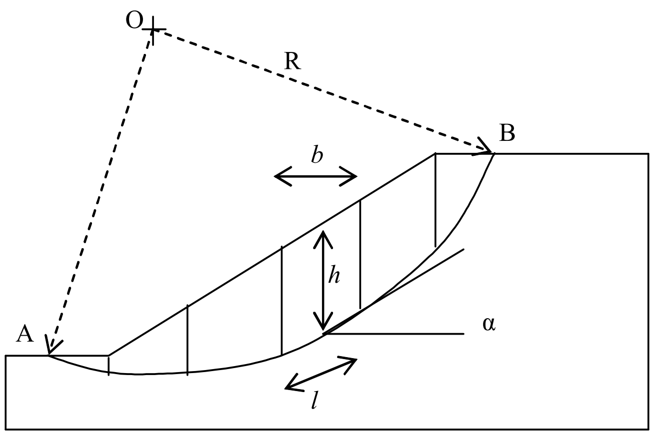
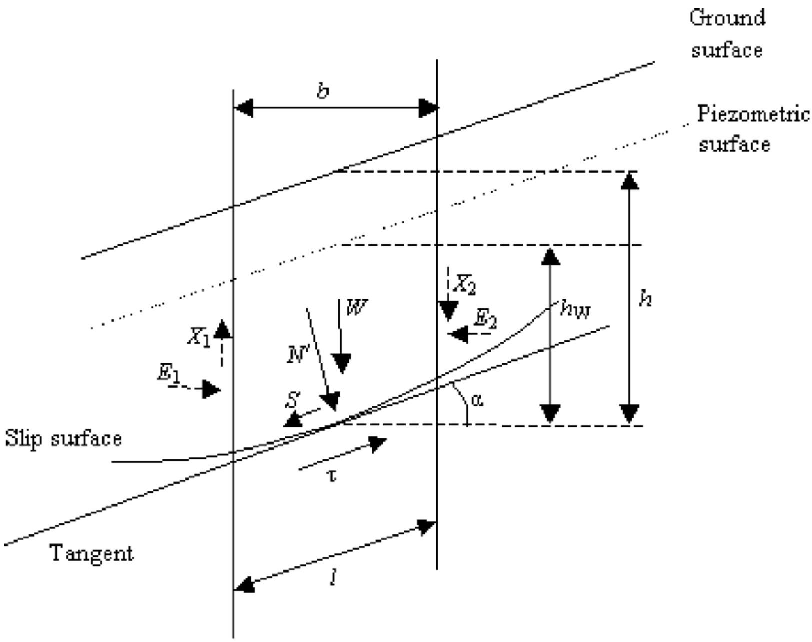


Figure 5-2. Method of slices. A circular slip surface of radius R, has centre O and intersection points at the ground surface of A and B. The soil mass above the slip surface is divided into a number of vertical slices of width *b* and varying height *h*. The base of each slice is assumed to be a straight line inclined at an angle α to the horizontal and with a length *l*.

The forces acting on a slice (Figure 5.3) are:

- The total weight of the slice, W = γbh where γ is the bulk unit weight of the soil.
- The weight of each slice induces a shear force parallel to its base, S = Wsinα.

- The total normal force on the base, N = σl.
- The total normal force is obtained from total normal stress, i.e., the effective normal force N′ = $\sigma' l$ and the water force U = ul where u is the pore water pressure.
- The shear force τl.
- The interslice forces, represented as total normal forces E_1 and E_2 and tangential shear forces X_1 and X_2.



Legend:

W	Weight of slice
h	Average height of slice
h_W	Head of water above slip surface
α	Angle of base of slice
l	Length of slip surface
b	Width of slice ($b = l\cos\alpha$)
N'	Effective normal force on slip surface
u	Water pressure = $\gamma_W h_W$
τ	Shear strength
X_1, X_2, E_1, E_2	Interslice forces

Figure 5-3. Forces acting on a slice.

For each slice, FOS is given by (from Figure 5.3):

$$FOS = \frac{\tau l}{W sin \alpha} \quad (2)$$

By applying the Mohr-Coulomb strength relationship, i.e., $\tau = c' + \sigma_n' \tan \phi'$ where τ = available shear stress, c' = effective cohesion, σ_n' = effective normal stress on the shear plane and ϕ' = effective angle of friction at the slip surface. Equation [2] can now be written as:

$$FOS = \frac{c'l + N' \tan \phi'}{W \sin \alpha} \quad (3)$$

where $N' = \sigma_n' l$.

The effects of the single slice may now be added to the adjacent slices to give the overall FOS for the slip surface.

$$FOS = \frac{\sum c'l + N' \tan \phi'}{\sum W \sin \alpha} \quad (4)$$

The value N' in Equation [4] may be determined by resolving forces, where $N' = W \cos \alpha - ul + (X_2 - X_1) \cos \alpha - (E_2 - E_1) \sin \alpha$, i.e.,

$$FOS = \frac{\sum (c'l + (W \cos \alpha - ul) \tan \phi' + [(X_2 - X_1) \cos \alpha - (E_2 - E_1) \sin \alpha] \tan \phi')}{\sum W \sin \alpha} \quad (5)$$

However, to solve Equation [5] assumptions must be made regarding the interslice forces. Table 5-1 shows the solutions to the interslice force assumptions made by Fellenius (1936), Bishop (1955), Janbu (1973) and Greenwood (1987).

NB., The FOS value must be determined for the surface that is likely to fail, i.e., the critical slip surface. It is therefore necessary to perform calculations for a considerable number of possible slip surfaces in order to determine the location of the critical slip surface.

Table 5-1. Solutions and assumptions to the Factor of Safety equation.

Method	FOS Equation	Assumptions
Fellenius	$\frac{\sum[c'l + (W\cos\alpha - ul)\tan\phi']}{\sum W\sin\alpha}$	Water surface is parallel to the slip surface, i.e., $(X_2 - X_1)\cos\alpha - (E_2 - E_1)\sin\alpha = 0$. NB. Considerable errors occur when steep base angles to the slice are combined with high water pressures (Turnbull and Hvorslev 1967; Greenwood 1983).
Bishop	$\frac{\sum\left[\frac{(c'b + (W - ub)\tan\phi')\sec\alpha}{(1 + (1/FOS_m)\tan\phi'\tan\alpha)}\right]}{\sum W\sin\alpha}$	Tangential interslice forces are equal and opposite ($X_1 = X_2$) and the normal interslice forces are not equal (E1 ≠ E2). NB. The value of FOS occurs on both sides of the expression, therefore an estimated value for FOS must be chosen on the right hand side to obtain a value of FOS on the left hand side. By successive iteration convergence on the true value of FOS is obtained.
Janbu	$\frac{\sum\left[\frac{(c'b + (W - ub)\tan\phi')\sec\alpha}{(1 + (1/FOS_f)\tan\phi'\tan\alpha)\cos\alpha}\right]}{\sum W\tan\alpha} x\, f_0$	Identical to Bishop except that the equation is expressed in terms of horizontal force equilibrium and a compensation multiplying factor is introduced (typically $f_0 = 1.05$).
Greenwood General	$\frac{\sum[c'l + (W\cos\alpha - ul - (U_2 - U_1)\sin\alpha)\tan\phi']}{\sum W\sin\alpha}$	Effective interslice forces analysed and water forces, U_1 and U_2, on the sides of the slice are taken into account, i.e., $(X'_2 - X'_1)\cos\alpha - (E'_2 - E'_1)\sin\alpha = 0$.

Greenwood General (with K)	$\dfrac{\sum\left(c'l+[W\cos\alpha-ul-(U_2-U_1)\sin\alpha+K\tan\alpha(W-ub)\sin\alpha]\tan\phi'\right)}{\sum W\sin\alpha}$	Inclusion of coefficient of horizontal earth pressure, K, influences position of critical slip surface (particularly in over-consolidated soils).

Horizontal force equilibrium

It is sometimes convenient to express the FOS in terms of horizontal force equilibrium (FOS_f), e.g., for slips involving a significant near horizontal movement or to relate to retaining wall design. The equivalent horizontal forces are determined for each slice of the analysis simply by dividing the numerator and denominator of the stability equation by cosα. The Greenwood General (Greenwood 1989, 1990; Morrison and Greenwood 1989), and Fellenius equations may all be converted to horizontal force equilibrium in the same way as the Bishop equation converts to the Janbu equation.

Confidence in the Factor of Safety

An acceptable FOS for a particular slope requires sound engineering judgment due to the multiple factors which must be considered. A qualified geotechnical engineer must be consulted in all cases. A FOS for a slope can only be determined when there is an appropriate method of analysis; flow slides and erosion are not readily analysed by these methods.

For each slope, two factors should be considered: (1) the consequences of failure occurring and (2) the confidence in the information available. When there is a risk to life and adjacent structures a higher FOS would be normally be chosen. A lower FOS is chosen when instabilities do not affect lives or structures. The FOS is very dependent on the complexity of the ground conditions, the quality of the data obtained from the site investigation and the certainty of the design parameters.

The FOS selected is very dependent on the confidence in the parameters selected for the analysis. For a slope on the point of failure a remedial action that increased the FOS calculated by back analysis[1] by say 5% from 1.00 to 1.05 would provide greater confidence than a calculated value of 1.05 based on estimated parameters. It should be noted that in accordance with recent European standards (BS EN1997-2 2007) 'partial' safety factors are now applied to individual parameters of stability equations to reflect the level of confidence in that parameter.

[1] A failed slope is considered to have a FOS of unity (1.0) at the time of failure. Using this knowledge and an appropriate method of analysis, a model of the slope at failure can be developed. The process by which the failure conditions are determined and the failure model is established is termed back analysis or back calculation (Duncan and Wright 2005).

UK recommendations for cuttings, natural slopes and embankments are for FOS between 1.3 and 1.4 for first time slides and a FOS of 1.2 for slides with pre-existing slip surfaces (BS6031 1981).

1.2 Vegetation factors in slope stability

In this chapter, we are primarily concerned with the stability of vegetated slopes or slopes that have the potential to be vegetated. The influences of vegetation on a slope and the modification of the basic stability equation to include the effects of vegetation are therefore discussed.

Figure 5.4 shows the additional parameters that need to be considered when incorporating vegetation into the stability analysis. Each additional parameter is explained in the following sections and values are suggested for different vegetation types for input in the stability analysis. The parameters are further discussed in Coppin and Richards (1990) and Greenwood et al. (2004).

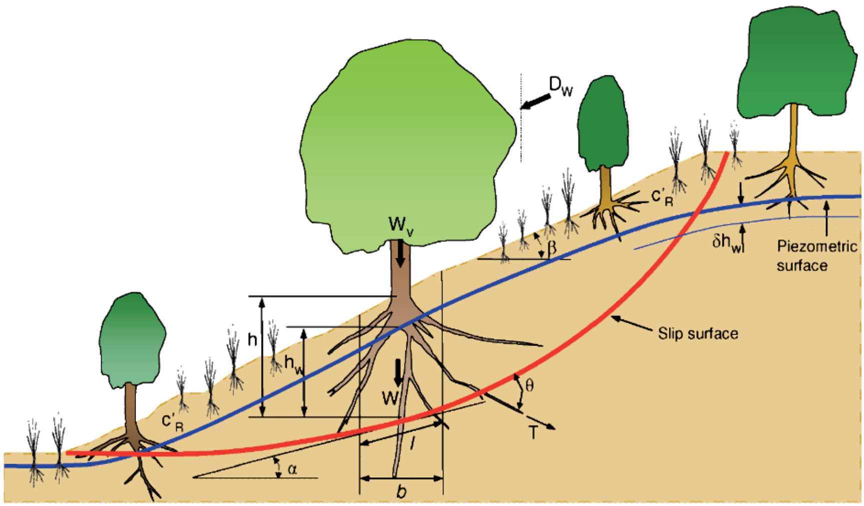


Figure 5-4. Forces exerted on a slope by vegetation (after Greenwood et al. 2004). Parameters: α – angle of slip surface; β – slope angle; c'_R – enhanced cohesion due to fine roots; D_w – wind force; *b* – width of slice; *l* – length of slice; h_z – height of slice above slip surface; h_w – height of phreatic surface above slip surface; δh_w – change in phreatic surface due to uptake of water by vegetation; W – total weight of soil slice; W_v – surcharge of vegetation; T – tensile force of roots acting on slip surface; θ – angle of roots to slip surface.

Enhanced cohesion, c'_R

The concept of effective cohesion in soils has received considerable attention with some researchers advocating that no true cohesion exists in clay soils (Schofield 1998, 1999; Goodman 1999). 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′ = 1–2 kPa. The actual value of c'_R input into the slope stability analysis can have considerable influence on the calculated FOS. Values of c'_R have been measured by researchers often based on direct *in situ* shear tests, back analysis or from root density and vertical root model equations (Table 5-2). Values vary from 1–25 kPa depending on the type of soil and vegetation. Tests carried out by Schmidt et al. (2001) show that lateral root cohesion ranges from 6.8–23.2 kPa for industrial forests with understory and deciduous vegetation, 25.6–93.4 kPa for natural forests dominated by coniferous vegetation and ≤10 kPa in clear-cut areas from the Oregon Coast Range (Table 5-3).

In situ shear apparatus (Figure 5.5) can be readily manufactured in the workshop and with a team of volunteers, a number of shear tests can be carried out in a day (Norris and Greenwood 2003; Norris 2005a, b; van Beek et al. 2005). Field tests will tend to give an indicative undrained strength increase due to the presence of fine roots but, for clay soils, the true effective parameters are more accurately obtained by back analysis or more sophisticated effective stress laboratory testing.

The use of enhanced c′ values is appropriate for grassed areas or areas of uniform vegetation where fine root distribution with depth is consistent and easily defined. In general, the reliable benefit of an enhanced c′ value will be limited to shallow depths.

Figure 5-5. Set up of *in situ* shear apparatus (Photo: J.E. Norris).

Table 5-2. Typical values for increases in soil cohesion (c'_R) due to roots (updated from Norris and Greenwood 2006).

Source	**Vegetation, soil type and location**	**Root cohesion c'_R (kPa)**
	Grass and Shrubs	
Wu[3] (1984a)	Sphagnum moss (*Sphagnum cymbifolium* L.), Alaska, USA	3.5 – 7.0
Barker[2] (1987)	Boulder clay fill (dam embankment) under grass in concrete block reinforced cellular spillways, Jackhouse Reservoir, UK	3.0 – 5.0
Buchanan and Savigny[1] (1990)	Understorey vegetation (*Alnus*, *Tsuga*, *Carex*, *Polystichum*), glacial till soils, Washington, USA	1.6 – 2.1
Gray[5] (1995)	Reed fiber (*Phragmites communis* Trin.) in uniform sands, laboratory	40.7
Tobias[2] (1995)	*Alopecurus geniculatus* L., forage meadow, Zurich, Switzerland	9.0
Tobias[2] (1995)	*Agrostis stolonifera* L., forage meadow, Zurich, Switzerland	4.8 – 5.2
Tobias[2] (1995)	Mixed pioneer grasses (*Festuca pratensis* Huds., *Festuca rubra* L., *Poa pratensis* L.), alpine, Reschenpass, Switzerland	13.4
Tobias[2] (1995)	*Poa pratensis* L. (monoculture), Switzerland	7.5
Tobias[2] (1995)	Mixed grasses (*Lolium multiflorum* Lam., *Agrostis stolonifera* L., *Poa annua* L.), forage meadow, Zurich, Switzerland	–0.6 – 2.9
Cazzuffi et al.[5] (2006)	Elygrass (*Elytrigia elongata L.*) Eragrass (*Eragrostis curvala* Nees) Pangrass (*Panicum virgatum L.*) Vetiver (*Vetiveria zizanioides* L.) all on clayey-sandy soil of Plio-Pleistocene age, Altomonto, S. Italy	10.0 2.0 4.0 15.0
Van Beek et al.[2] (2005)	Natural understory vegetation (*Ulex parviflorus* Pourret, *Crataegus monogyna* Jacq., *Brachypodium* var.) on hill slopes, Almudaina, Spain	0.5 – 6.3
Van Beek et al.[2] (2005)	*Vetiveria zizanoides* L., terraced hill slope, Almudaina, Spain	7.5
Mattia et al.[3] (2005)	*Lygeum spartum* L. *Pistacia lentiscus* L. *Atriplex halimus* L. all on eroded badlands in southern Italy	0.3 – 60 3.0 – 20.0 0.2 – 6.0

Norris[2] (2005a)	Mixed grasses on London Clay embankment, M25, England	~10.0
Mickovski et al.[5] (2007b)	*Lolium perenne* L., on agricultural soil	3.0 – 4.5
	Deciduous trees	
Endo and Tsuruta[2] (1969)	Silt loam soils under alder (*Alnus* P. Mill.), nursery, Japan	2.0 – 12.0
O'Loughlin and Ziemer[2] (1982)	Beech (*Fagus* sp. L.), forest-soil, New Zealand	6.6
Riestenberg and Sovonick-Dunford[4] (1983)	Bouldery, silty clay colluvium under sugar maple (*Acer saccharum* Marsh**)** forest, Ohio, USA	5.7
Schmidt et al.[3] (2001)	Industrial deciduous forest, colluvial soil (sandy loam), Oregon	6.8 – 23.2
Danjon et al.[3] (2007)	Mature *Quercus alba* L. on regolithic clays, Georgia, USA	0.01 – 63.0
	Conifers	
Swanston[1] (1970)	Mountain till soils under hemlock (*Tsuga mertensiana* Bong. Carr.) and spruce (*Picea sitchensis* (Bong.) Carr.), Alaska, USA	3.4 – 4.4
O'Loughlin[1] (1974)	Mountain till soils under conifers (*Pseudotsuga menziesii* (Mirb.) Franco), British Columbia, Canada	1.0 – 3.0
Ziemer and Swanston[3,5] (1977)	Sitka spruce (*Picea sitchensis* (Bong.) Carr.) - western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), Alaska, USA	3.5 – 6.0
Burroughs and Thomas[4] (1977)	Mountain and hill soils under coastal Douglas-fir and Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), West Oregon and Idaho, USA	3.0 – 17.5
Wu et al.[3] (1979)	Mountain till soils under cedar (*Thuja plicata* Donn ex D. Don), hemlock (*Tsuga mertensiana* Bong. Carr.) and spruce (*Picea sitchensis* (Bong.) Carr.), Alaska, USA	5.9
Ziemer[2] (1981)	Lodgepole pine (*Pinus contorta* Dougl. & Loud.), coastal sands, California, USA	3.0 – 21.0
Waldron and Dakessian[4] (1981)	Yellow pine (*Pinus ponderosa*) seedlings grown in small containers of clay loam	5.0

Gray and Megahan[3] (1981)	Sandy loam soils under Yellow pine (*Pinus ponderosa* Douglas. ex Lawson.), Douglas-fir (*Pseudotsuga menziesii*) and Engelmann spruce (*Picea engelmannii* (Parry.) Engelm.), Idaho, USA	~ 10.3
O'Loughlin et al.[2] (1982)	Shallow stony loam till soils under mixed evergreen forests, New Zealand	3.3
Waldron et al.[2] (1983)	Yellow pine (*Pinus ponderosa*) (54 months), laboratory	3.7 – 6.4
Wu[3] (1984b)	Hemlock (*Tsuga* sp.), Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and yellow cedar (*Thuja occidentalis* L.), Alaska, USA	5.6 – 12.6
Abe and Iwamoto[2] (1986)	*Cryptomeria japonica* D. Don (sugi) on loamy sand (Kanto loam), Ibaraki Prefecture, Japan	1.0 – 5.0
Buchanan and Savigny[1] (1990)	Hemlock (*Tsuga* sp.), Douglas fir (*Pseudotsuga*), cedar (*Thuja*), glacial till soils, Washington, USA	2.5 – 3.0
Gray[5] (1995)	*Pinus contorta* Dougl. & Loud. on coastal sand	2.3
Schmidt et al.[3] (2001)	Natural coniferous forest, colluvial soil (sandy loam), Oregon	25.6 – 94.3
Van Beek et al.[2] (2005)	*Pinus halepensis* Mill., hill slopes, Almudaina, Spain	–0.4 – 18.2

1. Back analysis. 2. *In situ* direct shear tests. 3. Root density information and vertical root model equations. 4. Back analysis amd root density information. 5. Laboratory shear tests.

Table 5-3. Lateral root cohesion derived from root area ratio and tensile strength values for different vegetation communities in Oregon, USA (after Schmidt et al. 2001).

Vegetation community	**Lateral root cohesion c'_R (kPa)**
Natural Forest Pit	94.3
Inferred Natural Forest	71.4
Natural Forest Blowdown Landslide	25.6
Industrial Forest Pit	23.2
Natural Forest Landslide	11.0
Industrial Forest Landslide	6.8
Clear-cut Pit	6.7
Clear-cut Landslide	2.7
Herbicided Clear-cut Pit	1.5

The mass of vegetation, surcharge W_v

The mass of vegetation is only likely to have a major influence on slope stability when larger trees (dbh* >0.3 m) are present since the weight of grass, herbs and shrub vegetation is comparatively insignificant. The loading due to a fully stocked forest for tree height between 30 and 60 m, is in the order of 0.5 to 1.5 kPa (Coppin and Richards 1990). A 30 m tall tree having a base trunk diameter of approximately 0.8 m is likely to have a weight of around 100 to 150 kN. Such trees located at the toe of a potential slip could add 10% to the factor of safety (Coppin and Richards 1990). Equally, if located at the top of a potential slip the FOS 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 effect 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 softening as available water is drawn in to satisfy the suction forces.

Wind loading, D_W

Wind loading is particularly relevant when considering the stability of individual trees but is 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 stand are sheltered to some extent by those at the edge.

Wind forces on single trees may be estimated from Brown and Sheu (1975) and Ancelin et al. (2004) by considering local pressures in relation to wind speed (i.e., $p_s = p\cos^2\beta$ where p_s = wind pressure normal to the tree, p = local wind pressure, β = slope angle). Wind loading on forested slopes may also be calculated by using Equation [6]:

$$p = 0.5\rho_a V^2 C_D \tag{6}$$

where p = wind pressure, ρ_a = air density in kg/m^3, V = wind velocity in m/s and C_D = dimensionless drag coefficient (Hsi and Nath 1970). Average wind speeds for Europe may be assumed from the wind resources map (Troen and Petersen 1989).

Soil strength increase due to moisture removal by roots, c'_s

Observations of moisture deficit around trees due to the effects of evapotranspiration and the problems this has caused for buildings and

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* - diameter at breast height

structures are well documented (e.g., Hunt et al. 1991; Biddle 1998). However when it comes to relying on tree and shrub roots to remove water and hence strengthen soil slopes it is not quite so straightforward. Vegetation trials on the M20 motorway, U.K., indicated large seasonal variations in moisture content (and hence the undrained soil strength) of the south facing trial area. These seasonal variations masked any effects the vegetation may have contributed to increased soil strength (Greenwood et al. 2001).

During particularly wet periods, the ability of plant 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 may well be.

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 provide pathways for roots to extend deeper into the soil in their search for moisture and nutrients. Vegetation may also promote unwanted desiccation cracks on highway roads (Figure 5.6).

Figure 5-6. Embankment shrinkage due to the presence of high water demand trees (mainly oaks) on the overbridge at Junction 12, M11, U.K. (Photo: Courtesy of C. Bull, URS Corporation Ltd, Bedford, U.K.).

Suctions and changes in pore water pressure due to vegetation, u_v

The moisture content and pore water pressures within a slope are closely related. Suctions or changes in pore water pressure can be measured over the long-term through the installation of tensiometers. Tensiometers installed on slopes are able to monitor and record the response of the ground suctions to rainfall events and periods of wet or dry weather (Greenwood et al. 2001). Indraratna et al. (2006) carried out numerical modelling of the matric suctions of native Australian vegetation used for stabilising railway corridors built over expansive clays and compressive soft soils. Indraratna et al. (2006) showed that the vegetation improves the shear strength of the soil by increasing the matric suction, and as a result curtailing slope movements.

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 10 – 40 MPa (see Chapter 4).

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 available force contribution from the roots can be measured by *in situ* pull out tests using hand digital force gauges or mechanical/hydraulic jacking apparatus (Figure 5.7, see Norris and Greenwood 2000, 2003 for procedure).

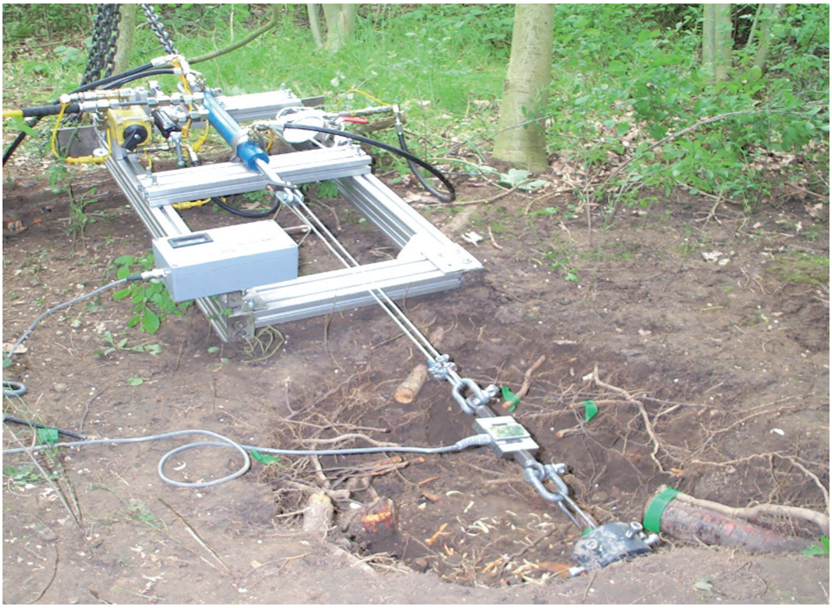

Figure 5-7. Root pull out apparatus (Photo: J.E. Norris).

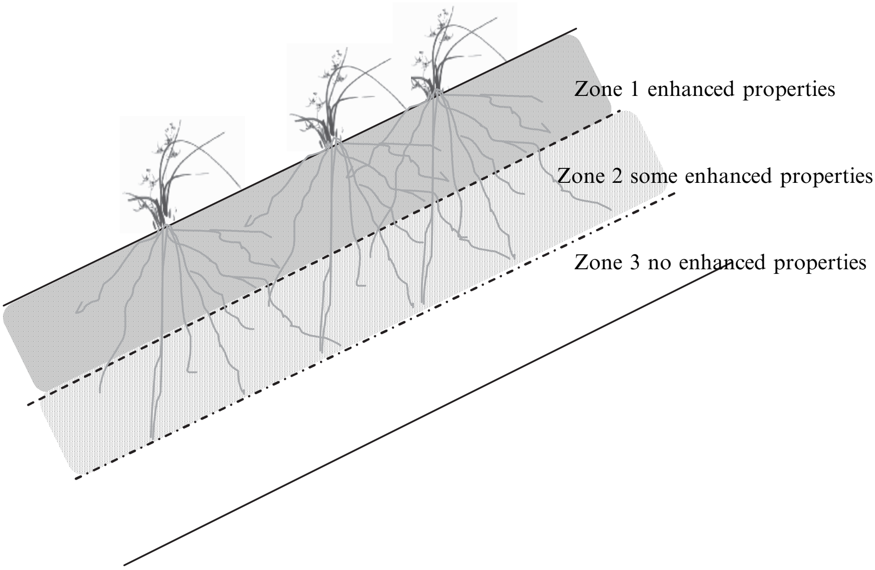

Figure 5-8. Zones of enhanced soil properties for grass and shrub vegetation cover (modified from Greenwood et al. 2003).

The maximum breaking force or pull out resistance of the roots and the associated root area ratio (root size and distribution) is used to determine the appropriate root reinforcement values for inclusion in Greenwood's General equation. The distribution of roots in a vertical trench wall profile of soil can be assessed by measuring the Root Area Ratio (RAR), i.e., the proportion of the cross-sectional area (CSA) of a sample section of soil that is occupied by roots.

The available root force acting on the base of the slice of the analysis, T, can be estimated by introducing the term T_{rd}, the available (design) root force per square metre across a particular plane (for example, the slip surface) within the soil. Values of T_{rd} may be assigned for different root zones evident beneath the ground surface (Figure 5.8). T_{rd} is based on the ultimate root force available across the plane considered, T_{ru} in kN (per square metre of soil), with a suitable safety factor due to the roots, FOS_r applied, i.e.,

$$T_{rd} = \frac{T_{ru}}{FOS_r} \tag{7}$$

T_{ru} may be estimated based on the observed or assumed root distribution and determination of characteristic resisting forces for the roots of varying diameters by root pull out and tensile strength testing (Norris and Greenwood 2000, 2003; Greenwood et al. 2004; Norris 2005a).

The natural evolution of plant roots is such that they are generally just sufficient to serve their purpose of maintaining stability against gravitational and wind forces. It has been observed that the pull out resistance of a root is likely to be only slightly less than the measured tensile strength of the root (Norris 2005b). The tensile strength of the root is therefore likely to be a reasonable indicator of the maximum pull out resistance available.

There is considerable uncertainty about root distribution in the ground and the resisting forces which are available in particular soil conditions. For this reason a high estimated value of FOS_r is recommended. Values of FOS_r of 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 (Greenwood et al. 2004). It may be possible to reduce the FOS_r as the root zones around the plant or tree are better characterised on a seasonal basis and more root pull out information becomes available.

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

$$T_{rd} = \frac{assigned\ ultimate\ root\ resistance \text{ x } root\ area\ (per\ sq.m.of\ soil)}{FOS_r} \tag{8}$$

The force T applicable to a slice of the stability analysis is given by Equation [9].

$$T = T_{rd}\, l \tag{9}$$

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

1.2.1 Stability analysis to include the influences of vegetation

The influences of vegetation on the FOS of a slope can be modelled by routine limit equilibrium stability analysis methods, e.g., the method of slices. Two methods of analysis (Greenwood's and Fellenius') are readily adapted for including the influences of vegetation. The addition of these influences of vegetation in Bishop, Janbu and other more sophisticated published solutions where the global FOS is applied to the shear strength parameters for each slice of the analysis results in unrealistic force scenarios for the slices where anchor and reinforcement loads are applied (Krahn 2001).

The Greenwood General equation (Greenwood 1989, 1990, 2006; Morrison and Greenwood 1989) is considered particularly appropriate for including vegetation because it takes full account of hydrological (seepage) forces to give a realistic estimate of the FOS for all types of slopes and slip surfaces:

$$FOS = \frac{\Sigma\left[c'l + (W\cos\alpha - ul - (U_2 - U_1)\sin\alpha)\tan\phi'\right]}{\Sigma W\sin\alpha} \tag{10}$$

where c' = effective cohesion at base of slice, l = length along base of slice, W = weight of soil, α = inclination of base of slice to horizontal, ϕ' = effective angle of friction at base of slice, u = water pressure on base of slice, U_1 and U_2 = interslice water forces on left and right hand side of slice.

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:

$$FOS = \frac{\Sigma\left[c'l + (W\cos\alpha - ul)\tan\phi'\right]}{\Sigma W\sin\alpha} \tag{11}$$

Equation [11] is the well known Fellenius equation (see Table 5-1) 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 FOS. The actual hydraulic conditions are therefore more correctly modelled using the Greenwood General equation (Morrison and Greenwood 1989).

The simple mathematical form of the Greenwood equations with the FOS simply expressed by a summation of restoring and disturbing moments or forces makes the inclusion of additional forces due to ground reinforcement, anchors or plant roots relatively straightforward (Equation [12]):

$$FOS = \frac{\Sigma\left[(c' + c'_R)l + ((W + W_v)\cos\alpha - (u + \Delta u_v)l - ((U_2 + \Delta U_{2v}) - (U_1 + \Delta U_{1v}))\sin\alpha - D_W\sin(\alpha-\beta) + T\sin\theta)\tan\phi'\right]}{\Sigma\left[(W + W_v)\sin\alpha + D_W\cos(\alpha-\beta) - T\cos\theta\right]} \tag{12}$$

It is noted that the tangential reinforcement force, $T\cos\theta$, in Equation [12], 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. This approach is statically correct in accordance with the force diagram. The differences in the calculated FOS by either approach are small with identical values calculated when FOS = 1.

Whilst the FOS in Equation [12] is expressed as a traditional ratio of restoring to disturbing forces, the equation may be adapted to include partial factors on each individual term in accordance with European codes of practice, Eurocode 7 (BS EN 1997-1 2004; BS EN 1997-2 2007).

Computer packages

A Microsoft Excel spreadsheet, known as 'SLIP4EX' (Greenwood 2006), was developed to compare routine methods of analysis for a given slip surface and to quantify the changes to the FOS due to the influences of the vegetation. This program is available from the author john.greenwood @ntu.ac.uk. Other computer software packages are available for slope stability analysis, e.g. Slope-W (http://www.geo-slope.com/), and STABL (http://www.ecn.purdue.edu/STABL/).

The energy approach

The energy approach was developed by Ekanayake et al. (1997) and Ekanayake and Phillips (1999a,b, 2002), to take into account the contribution of roots to soil strength for specific New Zealand soils. The method allows for the fact that roots can withstand large-strains during displacement of the soil-root system. To enable this method to be applicable to all cases, the original energy approach is generalised and a soil-water infiltration model is introduced.

In the stability analysis, the method incorporates the ability of tree roots to withstand strain during shear displacement. The characteristics of the shear stress–shear displacement curve obtained from an *in situ* direct shear test are used to find the total energy capacity of the soil-root system and the amount of energy exchanged up to the current displacement (Figure 5.9). The energy exchanged during the shearing process is directly related to the area between the stress-displacement curve and the x-axis. The total energy capacity of the soil-root system is the area under the soil with roots curve up to the shear displacement at peak shear stress.

The energy approach stability analyses method estimates the FOS using the energy associated with the root-soil shearing process. The FOS is defined by the ratio of energy already spent, up to the current shear displacement and the total energy capacity of the soil-root system. As the shear displacement is taken into account within the energy approach, this method will always overestimate the FOS compared to limit equilibrium methods.

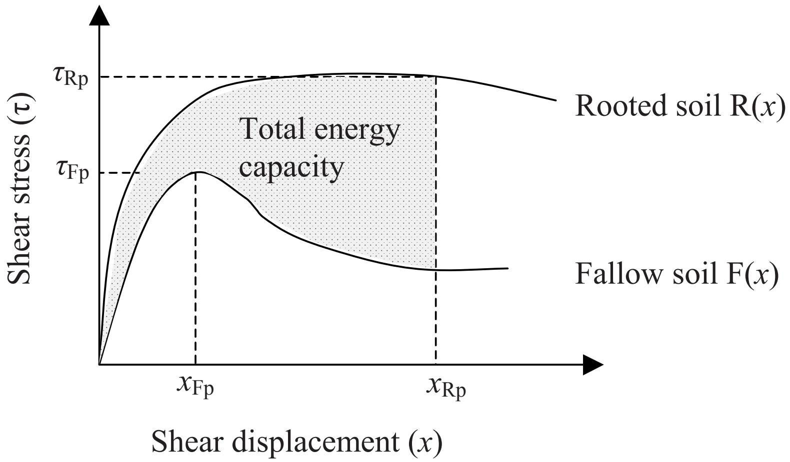

Figure 5-9. Ideal shear stress–displacement curves for fallow soil F(x) and soil with roots R(x). x_{Fp} is shear displacement at the peak stress (τ_{Fp}) for fallow soil and x_{Rp} is shear displacement at the peak stress (τ_{Rp}) for soil with roots. The shaded area between the two curves represents the total energy capacity of the soil-root system (after Ekanayake and Phillips 1999b).

Finite element models

Finite element modelling is based on a numerical approximation solution for solving problems represented by partial differential equations. The 'problem' or model is divided into discrete elements, each element is connected by nodes at the corners which form triangular or quadrilateral shapes. The behaviour of unknown variables is modelled at the nodes through appropriate polynomial equations. Two finite element packages which can be used to model vegetation and soil behaviour are PLAXIS and FLAC.

PLAXIS is a finite element package specifically intended for the two dimensional analysis of deformation and stability in geotechnical engineering projects (Brinkgreve 2002). Geotechnical applications require advanced constitutive models for the simulation of the non-linear, time-dependent and anisotropic behaviour of soils and/or rock. In addition, since soil is a multi-phase material, special procedures are required to deal with hydrostatic and non-hydrostatic pore pressures in the soil. PLAXIS can model the complex interaction between geotechnical structures and the soil.

The program allows for graphical input of geometry models, automatic mesh generation and 15-node triangular elements to model the deformations and stresses in the soil. Soil behaviour can be modelled using the Mohr-Coulomb model, advanced soil models such as the 'soil hardening' model, or other user-defined soil models (see Fredlund and Rahardjo 1993). Vegetation can either be modelled as geogrids for grass root networks, or as a series of anchors to replicate tree roots.

FLAC is a commercially available finite difference code with widespread application in geo-engineering (Itasca 2002). It mimics the stress-strain behaviour numerically so the strain-dependent effect of reinforcement can be simulated more realistically with fewer simplifying assumptions. Moreover, the root reinforcement model in FLAC offers the user to specify varying root and soil properties along the slope and the influence of the hydrology on the effective stress can be evaluated rigorously. This is highly advantageous since root reinforcement is influenced by the type and nature of the vegetation and local variations in soil conditions. An example of the use of FLAC2D to model root reinforcement can be found in van Beek et al. (2005).

2. HAZARD ASSESSMENT OF SOIL EROSION

2.1 Introduction

Soil erosion by water and wind affects both agriculture and the natural environment, and is one of the most important (yet probably the least well-known) of today's environmental problems (http://soilerosion.net/).

Soil erosion is an important issue and it concerns large areas of the terrestrial environment. It has a large economic impact as it degrades the most fertile part of the soil which negatively affects crop productivity (on-site effect) on the eroded areas and creates off-site problems, e.g., silting up of reservoirs. We should distinguish wind erosion from water erosion, as both processes are quite different both in process and their area of occurrence.

The occurrence of erosion is related to:

- rainfall characteristics (erosivity)
- soil material (erodibility)
- vegetation cover
- relief

Rainfall is more effective as an erosive factor when its intensity is high. High intensity rainfall events are mainly found in the Mediterranean, sub-tropical and tropical climate zones whereas in temperate zones these events are far less frequent.

In semi-arid and arid environments erosion is dominated by wind activity. Figure 5.10 shows the rainfall regimes under which both erosion types are dominant.

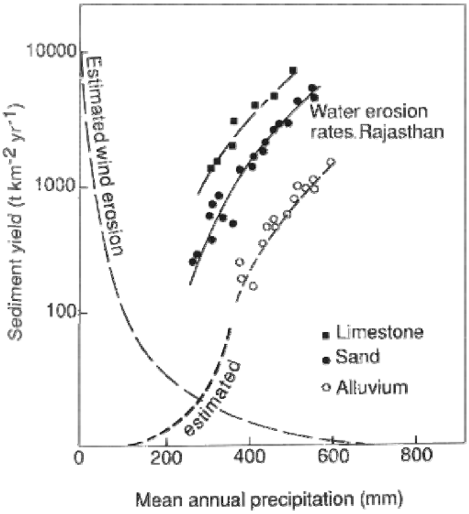

Figure 5-10. Measured and estimated rates of erosion by wind and water in different climatic conditions. From Cooke et al. (1993), reprinted by permission of the publisher.

Soil material

Porous and permeable materials are less susceptible to water erosion than finer textured soils. Silt and clayey soil may show high erodibility, although this latter factor is also influenced by soil organic carbon levels and soil mineralogy. Sandy soils may however be very vulnerable to wind erosion when organic matter is almost absent, or when water repellence is important.

Vegetation cover acts as a protective factor for the soil. It reduces the kinetic energy of the falling rain drops on the soil and it also promotes infiltration of water in the soil. Furthermore it also reduces overland flow velocities enhancing infiltration. Arable lands devoid of vegetation after ploughing can be extremely vulnerable to erosion.

Relief and terrain characteristics determine the slope gradients, slope curvature and slope length which all influence soil erosion. Steep slopes are more vulnerable to water erosion as well as long slopes. Areas with a long wind fetch are more vulnerable to wind erosion.

A broad discussion on these topics can be found in excellent textbooks on soil erosion such as that of Hudson (1979) and Morgan (2005).

2.1.1 Techniques of soil erosion assessment

Erosion can be assessed in many ways and a range of methodologies have been developed. These range from simple surveying techniques, long-term erosion measurement experiments, short intensive simulation experiments or GIS and remote sensing analysis. Assessment depends on the goal, and the time and money available as to which methodology can be applied. An excellent overview of erosion assessment and measurement is the work of Hudson (1993). This document is recommended by the authors as only a brief description is given of the main groups of methodologies that can be applied in the following text.

A general difference should be made between surveying techniques, which are more descriptive, but can be applied to larger areas and measuring techniques, which are more suitable to assess actual rates of erosion. In the first case, a good knowledge of the landscape and soils is necessary whereas in the last case, one should be fully aware that fine scale measurements cannot directly be extrapolated to larger areas as each process acting on the landscape has its own spatial and temporal process-domain, thresholds are involved in the geomorphic and hydrological response and connectivity between landscape units rules the movement of soil material through the landscape (Cammeraat 2004).

The use of erosion models is tempting but to be able to work with calibrated erosion models measured field data are necessary. Simple erosion models such as the empirical Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) are often used, but have their limitations as they are developed or calibrated for specific conditions, e.g., for the USLE: slopes < 6°; agricultural land and calibrated in standard bounded plots.

2.1.2 Surveying methods

Soil profile truncation

Soil erosion can be assessed from studying the development of the soil profile. The soil profile normally has a set of horizons that develop over long periods of time. When soil formation rates and or weathering rates are equal or larger than the soil erosion rate, soil profiles remain *in situ*. In the reverse case, soils will lose their upper soil horizons. Soils lacking a B and/or an A horizon are clear field indicators of accelerated erosion rates, which is often related to agricultural activity on sloping areas.

A survey of truncated soils may give a good indication of the spatial distribution of eroded soils and might help in determining the most affected areas or pinpointing areas at risk. A good knowledge of field pedology is prerequisite for applying this method.

Colluviation

Soils removed from sloping areas by soil erosion processes are often deposited at the foot of the slope in thick layers. Colluvial deposits can be recognized by the increased presence of organic matter, sometimes with an organic matter enriched layer of soil, often associated with charcoal fragments and a dirty coating around soil particles. Furthermore soil profile development is retarded because of the high deposition rate of colluvial material. As colluviation is often associated with soil profile truncation, field knowledge of soils is indispensable.

Soil surface properties

Careful observation of the soil surface is a good methodology to assess the occurrence of soil erosion processes. In Australia some interesting manuals have been published which enable the assessment of erosion and degradation of rangelands and grass areas under semi-arid conditions (Tongway 1994; Tongway and Hindley 1995). These methods can be good starting points to apply similar methodologies in other environments in combination with, for instance, indicator techniques (Imeson and Cammeraat 1999).

Surface wash can be observed by several indicators, for example, the exposure of lateral tree roots (Figure 5.11), and the presence of trees or shrubs standing on small mounds.

Slaking and Crusting is another important feature indicating reduced infiltration rates and erosion sensitive soils. Many different types of crusts exist which are well described in Casenave and Valentin (1989) for semi-arid environments or in Valentin and Bresson (1992) for soils in temperate climates.

Rilling when present is a clear sign of flow concentration with high soil material transport capacities. This type of erosion can easily by aggravated and lead to the formation of large gullies (Figures 5.12 and 5.13).

Tillage erosion is the result of tillage of soils on sloping areas, which causes a net downward transport of soil material (Quine et al. 1999; Takken et al. 2001). In upper slopes this can be seen from trees standing on isolated small hills and in lower slopes, trees might by partially covered at their base.

Figure 5-11. Sheet wash erosion in the Lake Baringo District in Kenya (Photo: E. Cammeraat).

Figure 5-12. Rill and gully erosion in the Lake Baringo District in Kenya (Photo: E. Cammeraat).

Figure 5-13. Rill erosion induced by ploughing (Guadalentin basin, Spain) (Photo: E. Cammeraat).

2.1.3 Measuring methods

Changes in soil surface levels

Changes in soil surface levels can be estimated by the use of erosion pins. Small pins are inserted in the ground, in such a way that they are permanently fixed and not subjected to vertical or lateral movement (soil shrinkage, creep). By measuring the height difference between the soil and the soil surface, soil surface lowering can be followed. Errors can be obtained by the influence of the pins themselves as they block air and water flow and the hydraulic regime around the pin is different compared to the open surface. Haigh (1977) discusses the possible errors resulting from applying this method.

In semi-arid environments, trees or shrubs may be seen standing on isolated small hills which could also be a sign of soil erosion, as the vegetation protects the surroundings from splash erosion. In other cases, this might indicate concentrated flow around vegetation clumps where plant roots protect the soil from water erosion.

A more modern method to determine the spatial distribution of erosion is the determination of the spatial pattern in the presence of radioactive nuclides like Caesium-137 derived from radioactive fall out (Walling and Quine 1990; Morgan 2005).

Measuring rill or gully erosion

The presence of rills and gullies in the landscape reflect also the activity of soil erosion processes. This activity can be estimated by the presence of or lack of vegetation, soil crusting and cryptogamic crusts. When well-established vegetation is present in a rill or gully (head) wall this indicates that it is not very active. Also, the presence of cryptogamic crusts indicates rather stable surfaces.

The development of gullies or rills may be followed over time. Measurements can be performed by placing a grid of reference markers in the surroundings of the gully (Hudson 1993). Measuring the distance between the gully head or wall to the reference points can give an indication of their growth. An indication of volumetric change and extension can be determined when the depth of the gulley is monitored.

Rills and gullies often occur in agricultural soils but are in most cases ploughed away by the farmer. In these areas, rilling and gullying is often associated with the direction of tillage (Figure 5.13). Erosion may increase enormously when contour ploughing is not applied.

Actual rates of erosion can also be determined by measuring the sediment output of a rill or gully in the same way as described below.

Measuring surface erosion

Erosion plots can be built to measure erosion rates. A soil surface is selected and the runoff and sediment produced by the area is collected in a gutter or trough. The plot can be bounded which is normally performed using the argument that the rate can be coupled to a fixed surface. However in reality this is usually not the case as the runoff and sediment are often not originating equally from the whole plot, but normally originates more from the area near the gutter. Long term experiments might suffer from sediment depletion as well. Bounding of the plot also limits the slope length, which is an important factor and it also excludes water coming from higher upslope to reach the gutter. However, many experiments use standardized bounded plot dimensions after the highly influential field experiments carried out in the US to support the USLE (Wischmeier and Smith 1978). Open (non-bounded) plots are also used and are more adjusted to the natural catchment areas present within a slope, but this deserves a more detailed topographic survey of the actual watershed that is drained by the gutter or troughs. In this case the origin of the water is also not clear due to the strong heterogeneity of soil surfaces.

Sediment can be sampled continuously during events by hand or with instruments, e.g., automatic samplers or turbidity meters, or on an event base.

Retention basins or catchpits. When small basins are present downstream of an eroding area, the amount of sediment delivered by this area can also be estimated from the soil trapped in small retention basins (Verstraeten and Poesen 2000). These are currently increasingly built to remediate off-site effects of erosion in sensitive areas but can also be designed especially for assessment purposes.

Rainfall simulations are often applied to measure erosion or runoff from soil surface areas. Rain in semi-arid environments does not occur frequently and intensity and amounts are unpredictable and variable. These problems can be overcome by rainfall simulation experiments (Figure 5.14). They have the advantage that they can be carried out under controlled conditions with regards to rainfall intensity and duration. Normally, rainfall is simulated over a plot where runoff and sediment are collected in a gutter or a trough. The big disadvantage of rainfall simulators is however, that the terminal velocity of the raindrops falling on the surface is critical with regards to their kinetic impact on the soil surface. Mostly, rainfall simulators are much lower than 9-10 m, which is normally the height for a drop to attain its terminal falling velocity. In particular, dripping plate simulators have this problem, e.g., Bowyer-Bower and Burt (1989). Simulators with nozzles have higher drop velocities as these drops are being produced under higher pressures. The spatial heterogeneity of the rainfall depth of simulators may also cause a problem (Lascelles et al. 2000). Upscaling is in any case a problem when working with fine scale measurements, as the erosion response is highly non-linear and complex, with different processes being dominant at different scales.

Figure 5-14. The drip-plate rainfall simulator (Amsterdam-type. Photo: E. Cammeraat).

Remote sensing and computer simulation methods

Many methods exist to predict erosion from fields or catchments using simulation models. As this topic is outside the purpose of this book, it is only briefly described and only one method is referred to from the vast literature on this topic. The most well known model is the USLE model which is simple and has been successfully applied on many agricultural soils (Wischmeier and Smith 1978). However it is not suitable for erosion assessment for larger areas such as watersheds (Wischmeier 1978). Many other soil erosion models exist on many different scales but they all highly depend on input data, which are often difficult to obtain.

Remote sensing is also increasingly used, by the interpretation of surface topography changes from aerial photography or by geodetic processing of high quality aerial photographs, e.g., Vandaele et al. (1996).

Change in topsoil properties can also be detected from spectral properties of soil surfaces and this can also be applied in regions where bare areas are present with characteristic differences in reflectance and spectral properties between the different soil horizons exposed, e.g., Metternicht and Fermont

(1998), Hill and Schütt (2000). Combining the results from both remote sensing and GIS is increasingly carried out.

3. STABILITY OF VEGETATION ON SLOPES

The stability of vegetation on slopes, especially forested slopes, is equally as important as the stability of the soil that the vegetation is planted in. This section reviews the hazards of wind and snow damage on forested slopes.

3.1.1 Windthrow Hazard

The practical problems and economic costs that result from windthrow of trees (Figure 5.15) has stimulated much research into tree root anchorage. This research effort is almost inseparable from the related topic of stabilisation of soil on slopes by tree roots. Much research on anchorage has focussed on the nature of the root-soil bond (for example, Waldron and Dakessian 1982; Operstein and Frydman 2000; Mickovski et al. 2007a). However, the effects of trees on soil stability are more complex than this. Trees provide considerable protection to slopes by sheltering the slope surface from the direct effects of wind and rain, by extracting soil water through transpiration, and by holding soil on both fine and coarse roots (Keim and Skaugset 2003). To maintain these benefits in forested slopes that are actively managed, consideration should be given to minimising windthrow at all stages during planning, managing and harvesting.

3.1.2 Soil loss from windthrow on slopes

Tree uprooting on slopes can lead to pits forming in the soil, in which water collects and infiltration is increased. However infiltration is not the only process leading to soil loss following windthrow. An investigation by Nicoll et al. (2005) predicted that for dense forest stands on steep slopes, where windthrow overturns root plates downslope, the potential downslope displacement of soil is in the order of 1800 m^3ha^{-1} from the displaced soil-root plates alone, even before additional soil is displaced by erosion processes associated with pits. This rate of soil loss is more than 1000 times the rate expected from standard forestry operations. As soil loss must be considered as an almost permanent degradation of the site, with considerably

Figure 5-15. Windthrow of plantation trees on a hill side in Scotland. Photograph courtesy of the Forestry Commission, UK.

greater long-term consequences in terms of forest sustainability than windthrow, soil conservation should become the primary consideration on such sites.

Nicoll et al. (2006) showed that species choice, soil type and rooting depth all influence anchorage. Therefore, these criteria may be used in any risk analysis to decide how forest stands should be designed, established and managed on steep slopes. Species with relatively good predicted anchorage or slow growth may be chosen for such sites, and the suitability of silvicultural treatments to be applied to them should be assessed based on the risks of windthrow and resulting soil loss. For example, particular care should be taken in applying thinning treatments or in respacing on vulnerable slopes (see Chapter 7).

3.1.3 Assessment of windthrow hazard

There are three basic approaches to the assessment of windthrow hazard: observational, mechanical and empirical (Cucchi et al. 2005; Mickovski et al. 2005). These are used either independently or in combination with each other:

- **Observational** approaches use a checklist of indicators.
- **Mechanical** approaches predict the critical wind speed for over-turning from winching and wind tunnel studies, and the probability of critical wind speed from wind mapping/modelling work.

- **Empirical** approaches use regression techniques to predict the probability of damage as a function of environmental and management variables.
- **Combined** approaches incorporate elements of the observational, mechanical and empirical approaches.

The wind risk system 'ForestGALES' (Geographical Analysis of the Losses and Effects of Storms in Forestry) is an advanced example of the combined approach. It was developed for conifer plantations, and is based on winching tests, wind tunnel studies, information on tree and soil characteristics, site wind exposure and wind climate (Quine and Gardiner 1998; Gardiner et al. 2004). The output gives the probability of damage to a stand over time. ForestGALES was designed for UK forests but has been adapted to work in parts of France, Denmark, Canada, Japan and New Zealand. It is adaptable for other countries, depending on availability of data on tree anchorage and wind climate. The ForestGALES decision support system is used by managers to minimise windthrow risk whilst optimising economic returns from timber. To do this, the manager must decide what level of risk he or she can accept and must always be prepared to accept some loss through windthrow.

Another method, which has been used in British Columbia, Canada, is based on the observational approach, but includes some elements of the empirical approach. This system uses windthrow risk assessment field cards to evaluate the windthrow risk (Mitchell 1998). In general, windthrow risk for an individual tree is a function of biophysical risk caused by the environmental factors and the treatment risk arising from the management factors. The environmental factors affecting windthrow are broadly grouped into topographic exposure, soil and stand properties, whilst management factors include the silvicultural management strategies (treatments) that cause change in wind loading on residual trees after the treatment.

ForestGALES and the British Columbia system are further described in Section 3.1.4.

Topographic exposure

Topography influences wind flow and, in turn, the vulnerability of trees to windthrow (Table 5-4). It takes into account the position of a single tree or a stand relative to prevailing winds. After the initial deceleration close to the ground upwind of ridges or hills, winds accelerate over their crests and often create separation bubbles behind them (Figure 5.16).

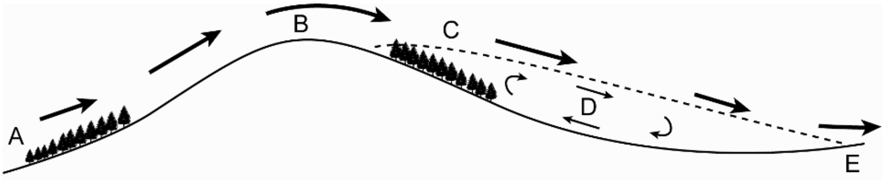

Figure 5-16. Features of the airflow over forested hills. A: presence of forest on lower slopes reduces wind speed at top; B: speed-up of the wind at summit; C: separation of flow in lee of hill encouraged by presence of trees; D: slack air in lee of hill; E: reattachment of flow downstream of hill (after Quine et al. 1995).

Table 5-4. The effect of tree/stand position and the prevailing wind direction on the vulnerability (low, moderate or high) to windthrow (adapted from Alexander 1987).

Topographic position of the tree or stand	**Wind direction**	
	Parallel	**Perpendicular**
Flat	Moderate	Moderate
Slope toe	Moderate	Moderate
Slope crest	High	Moderate
Knoll	High	Moderate
Side slope	Moderate	Moderate
Ridge	High	High
Shoulder	High	High
Saddle	High	High
Sheltered valley	Low	High

Simple assessments of topographic exposure can be made using Topex (Miller et al. 1987), which implies that the windiness of a site can be assessed with regards to its environment. For example, a slope aspect perpendicular to the prevailing wind direction is particularly exposed, but a valley parallel to prevailing winds may experience even higher wind speeds due to the funnelling effect.

Topex is calculated by summing the angle to the sky line at the eight principal cardinal points. High values indicate the presence of higher ground near the measurement site, and therefore the site is considered to be sheltered. These values are incorporated into the DAMS (Detailed Aspect Method of Scoring) system used in the UK as a measure of site windiness (Quine and White 1993). DAMS combines scores depending on region of the country (i.e., the wind zone of the location), elevation, Topex, aspect and funnelling.

Stand properties

Tree height

It has long been recognised that windthrow risk tends to increase with an increase in tree height (Cremer et al. 1982; Savill 1983; Miller 1985). Cremer et al. (1982) links this to three factors:

- An increase in stem height implies an increase in the turning moment applied to the base of the stem.
- Because wind speed increases with height inside and above the canopy, trees that are taller than their neighbours are more vulnerable.
- Trees in fully stocked stands have a decreasing diameter to height ratio as they grow, meaning that they are less tapered and hence more vulnerable to breakage or uprooting.

Irregular stand structure

Several empirical studies have investigated the effect of irregular stand structure on the risk of windthrow (Lanier 1994; Schütz 1997; Otto 2000; Dvorak et al. 2001). Mason (2002) reviewed these reports and found that although irregular stands are widely believed to be less vulnerable to wind damage, the many confounding factors, including site and topographical variation mean that this assumption may not always be correct. The ForestGALES model was used to assess windthrow risk in simulated irregular Sitka spruce stand conditions (Mason 2002). The main conclusion from this work was that the lower height over diameter (H:D) ratios of dominant trees, which is a widely recognised characteristic of irregular stands, helps improve tree and stand stability against wind damage. However, the extent of the increase in stability is mediated by site characteristics and by local wind climate. An effect perhaps more important than an increase in windthrow resistance is the greater plasticity of irregular stands. The faster recovery of wind-damaged irregular stands to their desired state was shown by Brang (2001) for protection forests in the Alps. This is why the risk of 'extensive' wind damage is considered to be lower in irregular, or uneven-aged, stands.

Existing damage in a stand

Signs of existing damage within stands can be indicative of the stand reaching a critical stage. Apart from obvious signs of blown or snapped trees, this can be indicated by evidence of pumping around trees (areas of wet ground-up soil on the surface where the tree is rocking), signs of extensive decay (rotten stems, fungi on stem), and compression creases in the bark of the tree.

However, if the damage is clearly associated with a specific localised problem, such as flooding caused by a spring or blocked drain or damaged roots or stems following harvesting operations, the stand may not be as vulnerable as the damage suggests. Evidence from studies in commercial plantations suggests that small windthrow gaps can remain with little expansion for many years under many circumstances (Quine 2002).

Windthrow at margins

An untreated forest edge is an abrupt barrier presented to the wind, and the edge trees are subjected to severe wind loading. The edge disrupts the flow for a distance of approximately 4-5 tree heights downwind at which point the flow direction is into the top of the forest and the trees are more vulnerable (Gardiner et al. 2005; Yang et al. 2006). This is where the gustiness of the wind suddenly increases, and where tree-scale damaging gusts have fully developed. If the edge trees are removed from a stand, for example, when widening a road, the remaining stand without the protection of large, windfirm edge trees, becomes particularly vulnerable to windthrow and damage is commonly observed even with relatively low wind speeds.

Windthrow and spacing

Similarly, the risk of windthrow increases after thinning as wind load on individual trees is increased and their capacity to dissipate energy by crown contact is decreased (Cremer et al. 1982; Savill 1983). It is considered that the effect is maximal immediately after the operation and then decreases with time (Lohmander and Helles 1987), as the trees adapt their growth in response to the wind, called “acclimative growth” (see Chapter 4) and thereby strengthen their anchorage (Nicoll and Ray 1996). Depending on its vigour, the stand may recover as soon as 2 – 5 years (Cremer et al. 1982; Savill 1983) but recovery times as long as 15 years have also been reported (Busby 1965).

The effect of initial spacing or early thinning is not as clear. Many authors consider that, through an increase in stem taper (or H:D ratio), wide spacing increases the stability of a stand (Cremer et al. 1982; De Champs 1987; Blackburn and Petty 1988; Galinski 1989; Maccurrach 1991; Valinger et al. 1993; Peltola and Kellomaki 1993). However, this conclusion was put into perspective by Gardiner et al. (1997) who showed that the evidence for an increase in stability was reasonable in relation to stem breakage but weak in relation to overturning. Gardiner et al. (1997) showed that with increased spacing, the bending moments transferred to the base of the stems increased faster than their capacity to resist them.

3.1.4 Windthrow Hazard Models

ForestGALES Model Description and Development

ForestGALES is a mechanistic model designed to replace the Windthrow Hazard Classification formerly used by the forest industry in the UK (Miller 1985; Gardiner and Quine 2000; Gardiner et al. 2004). The program calculates the critical wind speed to cause damage to a stand and the return period for that damage to occur. The use of such a model creates more flexibility for testing different forest management scenarios such as choice of cultivation, thinning options, drainage improvements, the impact of clearfellings, or the creation of retentions.

ForestGALES calculates the wind forces on trees within forest stands as a function of the tree characteristics. Firstly the model calculates the threshold wind speeds required for overturning and breakage as a function of tree height, diameter, current spacing, soil type, cultivation, drainage and choice of species (Gardiner et al. 2000, 2004). The average wind loading on each tree is calculated from the stress imposed on the canopy by the wind from a calculation of the aerodynamic roughness (z_0) and the zero plane displacement (d).

The resistance to breakage is based on the calculation of the bending moment required to cause the stress in the outer fibres of the stem to exceed the Modulus of Rupture (*MOR*) of the wood. It is possible to write an equation [13] to give the critical wind speed at canopy top for breakage:

$$uh_{break} = \frac{1}{kD}\left[\frac{\pi MOR \times dbh^3}{32\rho G(d-1.3)}\right]^{\frac{1}{2}}\left[\frac{f_{knot}}{f_{edge}f_{CW}}\right]^{\frac{1}{2}}\ln\left(\frac{h-d}{z_0}\right) \tag{13}$$

where $k = 0.4$ is Von Karman's constant, D is the average spacing between trees, G is an empirically derived gust factor, dbh is diameter at breast height, ρ is density, and h is mean tree height. The factors f_{knot}, f_{edge}, and f_{CW} account for the reduction in wood strength due to knots, the position of the tree relative to the edge and the additional load due to the overhanging weight of the crown respectively.

The resistance to overturning has been obtained from tree pulling experiments on almost 2000 trees (Nicoll et al. 2006) and is found to be strongly related to stem weight. A similar equation to Equation [13] can be derived for the critical wind speed at canopy top for overturning:

$$uh_{over} = \frac{1}{kD}\left[\frac{C_{reg}SW}{\rho Gd}\right]^{\frac{1}{2}}\left[\frac{1}{f_{edge}f_{CW}}\right]^{\frac{1}{2}}\ln\left(\frac{h-d}{z_0}\right) \tag{14}$$

where C_{reg} is a regression constant that is dependent on soil and rooting depth and SW is the stem weight of the tree. See Gardiner et al. (2000) for more complete details.

Once the critical wind speeds have been calculated it is necessary to predict the likelihood of such a wind speed occurring at that location. The wind climate model used in the program is obtained from the DAMS scoring system. The DAMS score is found to be well correlated to the Weibull '*a*' parameter (Quine 2000) and the Weibull '*k*' parameter is assumed constant. The Weibull distribution is used to derive the extreme wind speed probability distribution (ESDU 1987) and hence the probability of occurrence of any wind speed. These probabilities are transformed into return periods for both overturning and breakage expressed in the average number of years likely to occur before damage.

Future probabilities of damage (Figure 5.17) are calculated with the aid of yield models (Edwards and Christie 1981). These allow the stands to grow in time so the program can estimate the annual probabilities for damage at different time steps. The temporal dimension of the model is particularly important as it allows estimation of the changing risk during the life of the crop, and for testing the best silviculture practices that may maintain the stability of the trees.

The first commercial release of the ForestGALES decision support system in 2000 was a purely non-spatial version. A second version has since been released which incorporates improved wind climatology, and a fully integrated GIS version of the model (Figure 5.18) is currently under development.

The GIS version will allow a visual analysis of the implications of silviculture strategies in terms of wind risk, such as thinning, retentions, design of felling coupes, new forest roads or the effect of clearfelling of neighbouring stands (edge effect).

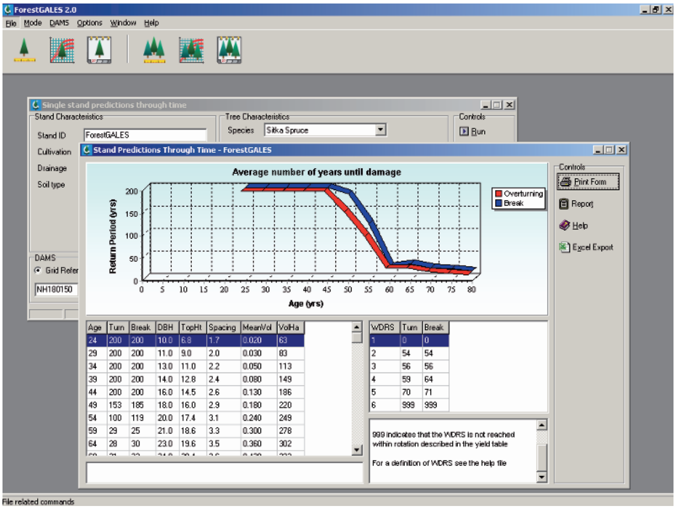

Figure 5-17. Example output screen from ForestGALES with the calculated return period displayed in the graph. Illustration courtesy of the Forestry Commission, UK.

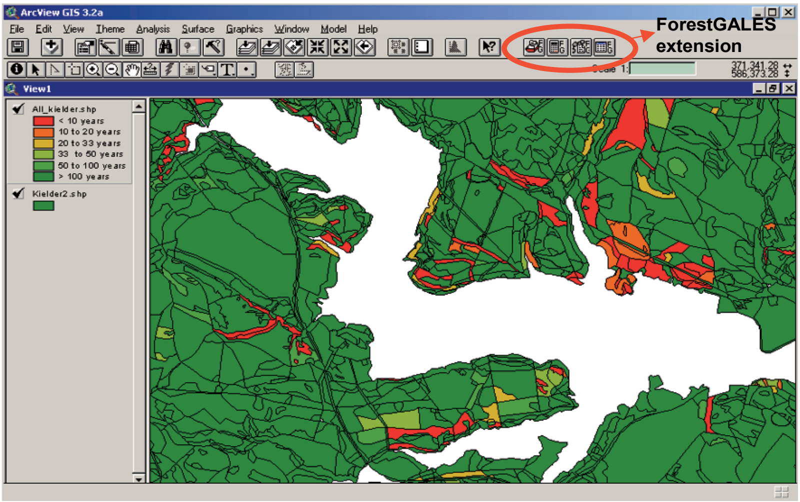

Figure 5-18. The ForestGALES extension to ArcView GIS showing different levels of risk for part of Kielder forest in Northern England, UK. Illustration courtesy of the Forestry Commission, UK.

British Columbia System

The Canadian British Columbia (BC) Ministry of Forests diagnostic method is observational but includes some elements of the empirical approach. According to this classification, windthrow risk for an individual tree or a stand can be calculated as:

Windthrow Risk = Biophysical Risk + Treatment Risk

In this assessment, the **'Biophysical Risk'** is the combination of the topographic exposure, soil characteristics and stand hazard components representing the intrinsic windloading and wind stability of trees on the site prior to treatment. The **'Treatment Risk'** represents the way in which a particular treatment increases or decreases the windloading or wind resistance of trees, while the **'Windthrow Risk'** is a combination of the biophysical risk and the treatment risk and represents the likelihood of damage from endemic winds (Table 5-5).

Topographic exposure hazards are assessed on a large- and mid-scale, as well as on the base of the tree/stand position on the slope. This assessment is based on the principles of Alexander (1987).

Soil characteristics are included in the assessment since the strength of anchorage is a function of root-soil mass, root-soil bond or shallow soils and drainage. Trees with unrestricted root systems (in coarse alluvial/colluvial soils, with depth of rooting >0.8 m with good drainage) will have a low risk of windthrow, while root systems with impeded growth (in fine textured soils with rooting depth <0.4 m, impeded by high water table or impenetrable soil layer, with poor drainage) bear a high risk of windthrow.

Stand characteristics and exposure to prevailing winds are also assessed knowing that the risk increases with the mean tree height, H:D (stem taper) ratio, stand density, and the amount of inside-stand damage and decreases in multi-layered stands or in stands with high live crown ratio. Wide openings >5 tree lengths and those oriented downwind at right angles are most hazardous and upwind openings at right angles which are smaller than 2 tree lengths are of low risk. Commercial thinning of more than 50% of the basal area is considered as highly hazardous management strategy.

The first box grid of Table 5-5 integrates topographic exposure and soil risks which are intrinsic and constant, to yield 'Site Risk'. The site risk is integrated with stand risk, which changes as stands grow and management practices are applied. When brought together in the second box grid, they yield 'Overall Risk'. The results of the biophysical risk assessment should be checked in the field during the 'calibration' step and adjusted if necessary (Mitchell 1998).

Table 5-5. Diagnostic windthrow risk assessment method based on evaluation of the tree/stand topographic exposure, soil characteristics and stand characteristics (adapted from British Columbia Ministry of Forests 1999). L = Low, M = Moderate and H = High risk.

Site Risk		**Topographic Exposure**		
		Low	**Moderate**	**High**
Soils	Low	L	M	M
	Moderate	M	M	H
	High	M	H	H

Overall Risk		**Site Risk**		
		Low	**Moderate**	**High**
Stand	Low	L	M	M
	Moderate	M	M	H
	High	M	H	VH

BC Ministry of Forests recognises that the best practices against high windthrow risks should include:

- a statement of windthrow management objectives
- consideration of windthrow risk
- inclusion of strategies to minimize and recover windthrow
- identification and evaluation of windthrow risk
- integration of windthrow risk into choice of silvicultural system
- calculation of the **'Windthrow Impact'**, referring to the potential harm windthrow could cause if it occurs. The impact is negative if wind damage results in management objectives not being met. If some level of damage is acceptable, this should be indicated in the original silviculture prescription.

3.1.5 Tree stability under snow

In Europe, hundreds of millions of euros are lost annually because of snow and wind-associated damage to forests. The type of forest growing on a slope and its resistance to snow loading can also influence the likelihood and magnitude of avalanches occurring. Damage to single trees, and more importantly to forest stands, leads not only to losses of high-quality and high-value timber but also to detrimental insect attacks on the remaining stands and reduced seed production amongst the older trees. Unscheduled and costly thinnings are often a consequence of severe snow damage (Makinen and Isomaki 2004; Rochette et al. 2004; Seki et al. 2005; Tremblay and Begin 2005).

Snow accumulation on trees is highly dependent on the climatological and topographical conditions including:

- temperature: influences snow moisture content and, in turn, the degree to which it can stick to the branches and needles
- wind: causes the snow to be shed but also leads to large accumulations of wet snow (late autumn or early spring), rime, or freezing rain
- geographic location and topography: affect the occurrence of damaging forms of snow, e.g., coastal locations and moderate to high elevations usually get large snow accumulations
- slope angle and aspect play a less important role but the evidence on the role of aspect is contradictory.

The severity of snow damage is related to tree characteristics that control the overall stability:

- stem taper and crown characteristics: slightly tapering stems, asymmetric crowns and rigid horizontal branching are highly hazardous
- species: due to coupling with the specific location, the hazard of failure for a particular species can not be clearly defined
- stand and forest management: can alter the hazards posed by the snow through choice of regeneration, tending, thinning and rotation.

For more information regarding the stability of trees under snow, the reader is referred to the following texts: Paatalo et al. (1999); Paatalo (2000); Peltola et al. (1997, 1999, 2000).

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