SLIP4EX – A program for routine slope stability analysis to include the effects of vegetation, reinforcement and hydrological changes.

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Short running title: 'SLIP4EX – Slope stability'

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Abstract: SLIP4EX is a straightforward computer program developed in connection with the EU funded ECOSLOPES project for routine stability analysis and the assessment of the contribution of vegetation to slope stability. The slope section is drawn up and dimensions and parameters are fed in to the Microsoft Excel based program for stability calculations and comparisons of Factors of Safety using different methods of analysis (Bishop, Janbu, Fellenius, Simple, Greenwood). The background and assumptions involved in the derivation of each of the methods is briefly described.

The simplicity of the program enables the user to understand the nature of the analysis, explore the parameter assumptions made and compare the different methods of analysis. Soil reinforcement by geosynthetic layers or anchors, and vegetation effects of enhanced cohesion, changed water pressures, mass of vegetation, wind forces and root reinforcement forces are readily included in the analysis. The program is freely available on request from the Author.

Keywords: hydrology, reinforcement, slopes, stability analysis, vegetation,

1. Introduction

SLIP4EX is a computer program for slope stability analysis, developed in connection with the European Commission funded 'ECOSLOPES' project to help assess the contribution of vegetation to slope stability (www.ecoslopes.com). It is based on the earlier SLIP3 'Fortran' program (Greenwood, 1986; Greenwood and Zytynski, 1993). The slope section is drawn up and dimensions and parameters are fed in to the Microsoft Excel based SLIP4EX program for stability calculations and comparisons of Factors of Safety using different methods of limit equilibrium analysis by the method of slices (Bishop, Janbu, Fellenius, Simple, Greenwood).

The simplicity of the program makes it ideal for preliminary problem analysis. It enables the user to understand the nature of the analysis, explore the parameter assumptions made and compare the different methods of analysis. Geosynthetic reinforcement may be included and vegetation effects such as enhanced cohesion, changed water pressures, mass of vegetation, wind forces and root reinforcement forces are readily included in the analysis.

The SLIP4EX program is freely available on request from the Author.

The use of the SLIP4EX program is illustrated by an example of a vegetated slope. The notation and the basis for the stability equations used in the spreadsheet are given in the Appendix to the Paper.

2. Example application of SLIP4EX to determine the Factor of Safety of a vegetated slope

2.1 Initial calculation without vegetation

The stability problem is drawn out to scale with the single slip surface defined as shown in Figure 1. Slice dimensions (up to 3 soil layers are permitted) and the angles between the base of each slice and the horizontal, are scaled from the diagram and appropriate soil and water parameters assigned for each slice as indicated in Table 1. The notation used and details of the dimensions are given in the Appendix (Tables A1, A2 and Figures A1, A2 and A3).
The prepared slice data is then input manually into the SLIP4EX spreadsheet program which calculates the forces acting on each slice of the analysis and the total forces acting on the slip surface. It calculates the Factor of Safety of the slip surface by the different methods commonly used by geotechnical engineers (Table 2). The spreadsheet currently has provision for up to 15 slices to be used.

The Appendix presents a brief review of the different assumptions relating to each method (Greenwood General, Greenwood General with K as input, Simple, Simple with K as input, Fellenius (Swedish), Bishop, and Janbu). The Factor of Safety is calculated both in terms of moment equilibrium and horizontal force equilibrium where appropriate. The iteration for the Bishop and Janbu solutions is done manually in this version by re-inputting the output Factor of Safety until the output value = input value. Automatic iteration can be done on the spreadsheet by addition of more columns.

There is an option in the Greenwood General and Simple methods to assess the additional effects of horizontal earth pressures on the calculated Factor of Safety by assigning an earth pressure coefficient (K value) to each slice. This would be particularly relevant for deeper slip surfaces in overconsolidated soils (Finlayson et al., 1984; Greenwood, 1985; Greenwood et al., 1985). It is conservative to assume K=0.

Once input, as for all spreadsheet work, parameters can readily be changed to demonstrate their sensitivity and influence on the calculated Factor of Safety.

2.2 Including the effects of vegetation

The parameters relating to the effects of vegetation (Table A2) may be included in the analysis. Appropriate additional parameters are assigned to each slice as indicated in Table 3 and input to the spreadsheet. In this example an additional tensile root reinforcing force is assumed to act on the base of each slice (in exactly the same way that a geosynthetic layer would contribute to stability). The derivation of this force is demonstrated in Section 3. In the example, the fine roots are assumed to have no influence on c′, but the piezometric head is assumed drawn down by 0.1 m under the influence of the vegetation.

The changes in the Factor of Safety due to the effects of the vegetation (or reinforcement or hydrological changes) are calculated in sheet 2 of the spreadsheet (Table 4). The effects are added to the General, Simple and Swedish equations but not the Bishop and Janbu methods where the iterative process and imposition of the Factor of Safety on to each slice in the stability equations does not permit easy inclusion of the additional forces.

In this example the vegetation has increased the calculated Factor of Safety from 1.08 to 1.21 (General method, Greenwood et al., 2003). It is emphasized that the assumptions made for the vegetation effects and hydraulic changes are to illustrate the application of the stability analysis and should not be applied to particular situations without appropriate investigation and testing.

3. Note on calculation of available root force, T, acting on each slice

Whilst the SLIP4EX spreadsheet is applicable to all stability calculations, it was developed with the intention of including vegetation effects. It may be helpful to describe the way in which a typical available root force is assigned in the above example following the procedure recommended by Norris and Greenwood (2000) and Greenwood et al. (2001 and 2004).

The available root force acting on the base of each slice, T, is calculated by the equation, $T = T_{rd} \times \ell$ where T_{rd} is the available root force per square metre of soil and ℓ is the length of the slip surface.

Typically from observation and tests, assuming 4 roots of 12.5 mm diameter, each having an ultimate pull out resistance of 8 MN/m^2, cross each square metre of soil at 1.2 m depth. The ultimate root force per square metre across the slip plane, T_{ru} would be given by:-

$T_{ru} = 4 \times \pi \times 0.0125^2 \times 8 \times 1000 / 4$ = approx 4 kN per square metre of soil

Applying a partial Factor of Safety of 8 to allow for uncertainty in root distribution and incompatibility of failure strain between the root and the soil (Greenwood et al., 2003), the design root force per square metre, T_{rd}, is given by:- $T_{rd} = T_{ru} / 8 = 4/8 = 0.5$ kN/m^2

Root forces, T, for each slice may therefore be calculated as follows:-

Slice	**T_{rd} kN/m^2**	**ℓ (approx) m**	**$T = T_{rd} \times \ell$ kN**
1	0.5	1.9	0.95
2	0.5	10	5
3	0.5	1.2	0.6

The effective angle between the operational roots and the slip surface, θ, is assumed to be 45°. Parametric studies on both geosynthetic and root reinforcement (Greenwood, 1990; Norris and Greenwood, 2003) have indicated that the calculated resistance due to the (root) reinforcement is not particularly sensitive to θ because as the enhanced normal component acting across the slip surface decreases, the tangential component, will increase.

As more investigation, testing and monitoring of vegetation is carried out, it should be possible to better define the vegetation related parameters and the partial Factor of Safety applicable to root forces for particular sites.

4. General application of SLIP4EX

SLIP4EX is intended as an easily accessible and available program to help gain an initial understanding of a slope problem and the main influences on stability. The less experienced practitioner can develop a feel for the aspects of the stability analysis and explore different mechanisms of failure before progressing to more sophisticated search programs to find critical slip surfaces. It is valuable as a student learning aid because the engineering process of drawing the slope, deciding on slip surfaces and assigning appropriate parameters is all kept under the user's control. Another application is where a particular slip surface generated by a commercial search program requires an independent check and further study of the significance of the assumed parameters.

Sheet 3 of the SLIP4EX spreadsheet provides opportunity to use the Excel plotting facilities to demonstrate aspects of the calculated output. For example the calculated restoring forces may be displayed for each slice for each of the methods of calculation.

5. Future Developments

Whilst SLIP4EX is particularly valuable to help gain an understanding of the stability problem, it is recognised that the next stage is to set up the full slope model and to run a search program to find the most critical slip surface. An 'automated' version of SLIP4EX (SLIP6EX) in which the problem is set up on the computer, slice dimensions and properties automatically assigned and the critical slip surface (circle) identified, is currently under development in collaboration with Rens Van Beek (personal communication).

Copies of the development version of SLIP4EX together with guidance notes are available by email request to john.greenwood@ntu.ac.uk. As a non commercial package this is provided with no guarantees, backup or support. Any suggestions for improvement or additions will be welcomed by the author.

APPENDIX - Notation and equations used in SLIP4EX spreadsheet

The notation used and details of the dimensions are given in Tables A1 and A2, and Figures A1, A2 and A3.

The equations used in the SLIP4EX spreadsheet are derived from the basic limit equilibrium stability equation (Lambe and Whitman 1969):-

$$F = \frac{\text{Restoring force (available shear strength)}}{\text{Disturbing force (shear force)}} = \frac{\sum(c'\ell + N'\tan\phi')}{\sum W\sin\propto}$$

By resolving forces to determine N′ (Figure A2), the full stability equation based on effective forces is obtained (See Greenwood, 1987; 1989):-

$$F = \frac{\sum\left(c'\ell + \left[W\cos\propto - u\ell - (U_2 - U_1)\sin\propto + (X'_2 - X'_1)\cos\propto - (E'_2 - E'_1)\sin\propto\right]\tan\phi'\right)}{\sum W\sin\propto} \quad \text{.... (1)}$$

In order to find a solution, assumptions must be made about the 'unknown' interslice forces X′ and E′.

Assumption 1
A reasonable assumption is that the resultant of the effective interslice forces is parallel to the base of the slice, i.e. in the direction of movement – a logical assumption as failure progresses.

i.e. $(X'_2 - X'_1)\cos\propto - (E'_2 - E'_1)\sin\alpha = 0$ .... (2)

This gives the **General equation** (See Greenwood, 1987; 1989; Morrison and Greenwood, 1989)

$$F = \frac{\sum\left[c'\ell + (W\cos\propto - u\ell - (U_2 - U_1)\sin\propto)\tan\phi'\right]}{\sum W\sin\propto} \quad \text{.. (3)}$$

Assumption 2
An alternative assumption is to ignore vertical interslice forces or at least assume they are equal and opposite (i.e. assume $(X_2' - X_1') = 0$ as Bishop (1955) and others do) - a reasonable

assumption when the slip mass is acting as a single unit - and assume that the effective horizontal interslice forces, E'_1 and E'_2, relate to the horizontal earth pressure.

i.e. $\sigma_h' = K\sigma_v'$ where K is the coefficient of lateral earth pressure.

Assuming K is constant with depth and constant water table conditions

$E_1' = K\gamma' h_1^2/2$ and $E_2' = K\gamma' h_2^2/2$ ....(4)

$\therefore\ E_2' - E_1' = K\gamma' h_2^2/2 - K\gamma' h_1^2/2 = K\gamma'/2\,(h_2^2 - h_1^2)$

$= K(\gamma_b - \gamma_w)\,(h_2 - h_1)(h_2 + h_1)/2$ ....(5)

but for <u>level ground surface</u> $h_2 - h_1 = -b\tan\alpha$ and $(h_2 + h_1)/2 = h$ (average height)

$\therefore\ E_2' - E_1' = -K\tan\alpha(\gamma_b h - \gamma_w h_w b)$
$= -K\tan\alpha(W - ub)$ .... (6)

for <u>sloping ground surface</u>, parallel to a slip surface, $h_2 - h_1 = 0$ and the term reduces to zero.

It is therefore reasonable to assume the general application of the term (6) for $E_2' - E_1'$ and to assign appropriate values of K depending on the location of the slip surface.

The **General equation to include an estimation of the horizontal interslice force based on 'K'** is therefore :-

$$F = \frac{\sum\left(c'\ell + \left[W\cos\alpha - u\ell - (U_2 - U_1)\sin\alpha + K\tan\alpha(W - ub)\sin\alpha\right]\tan\phi'\right)}{\sum W\sin\alpha} \qquad (7)$$

This equation (7) is consistent with Mohr – Coulomb retaining wall analysis theory.

For the particular case of horizontal water surface across the slice (static water conditions), from the slice geometry, $U_2 - U_1 = -ub\tan\alpha$, and equation (7) becomes:-

$$F = \frac{\sum\left(c'\ell + \left[W\cos\alpha - u\ell + ub\tan\alpha\sin\alpha + K\tan\alpha(W - ub)\sin\alpha\right]\tan\phi'\right)}{\sum W\sin\alpha}$$

which reduces to

$$F = \frac{\sum\left(c'\ell + \left[(W - ub)(1 + K\tan^2\alpha)\cos\alpha\right]\tan\phi'\right)}{\sum W\sin\alpha} \qquad (8)$$

Equation (8) is the **Greenwood Simple equation (K as input)** derived from the in-situ effective stress state based on Mohr circle / Coulomb criteria (Greenwood, 1983).

The value of K in equations (7) and (8) may be assigned for a particular situation. For example, a value of K=0 is appropriate where the slip surface is parallel to the slope and a value of $K=K_0$ may be appropriate for slip surfaces passing through the slope foundation (Greenwood, 1985; Greenwood et al., 1985; Finlayson et al., 1984).

The **Greenwood Simple** equation (9), is derived from equation (3) assuming a consistent horizontal water surface across the slice (Greenwood, 1983; Coppin and Richards, 1990) (i.e. $U_2 - U_1 = -ub\tan\alpha$)

or from equation (8) assuming K=0

$$F = \frac{\sum\left(c'\ell + \left[(W-ub)\cos\propto\right]\tan\phi'\right)}{\sum W\sin\propto} \qquad \text{.. (9)}$$

The basic Simple equation (9) is readily applied and is appropriate for routine analysis where slope, strata and groundwater conditions are not known in any detail. It gives sensible values of the calculated Factor of Safety in most situations.

The **Swedish equation** (Fellenius, 1936) is derived from the general equation (3) by making the assumption that the water surface is parallel to the slip surface (Greenwood, 1987; Morrison and Greenwood, 1989)

i.e. $U_2 - U_1 = 0$ therefore equation (3) becomes:-

$$F = \frac{\sum\left[c'\ell + \left(W\cos\propto - u\ell\right)\tan\phi'\right]}{\sum W\sin\propto} \qquad \text{.. (10)}$$

This equation (10) is shown to give considerable error when steep base angles to the slice are combined with high water pressures (Turnbull and Hvorslev, 1967; Greenwood 1983). It is generally conservative. It is ‘correct’ only for the theoretical continuous slope situation with seepage parallel to the slope where it is appropriate to assume $U_2 - U_1 = 0$.

The Bishop equation (Bishop 1955) is :-

$$F = \frac{\sum\left[\frac{\left(c'b + (W-ub)\tan\phi'\right)\sec\alpha}{(1+(1/F_m)\tan\phi'\tan\alpha)}\right]}{\sum W\sin\propto} \qquad \text{.. (11)}$$

This equation may be related to the general equation (3) but in general the assumptions do not correspond with the real distribution of the inter slice pore water forces (Morrison and Greenwood 1989). The Bishop solution is prone to errors and the equation can become mathematically unstable for high values of α (Turnbull and Hvorslev, 1967; Greenwood, 1983; Krahn, 2001). It may consequently over-estimate the Factor of Safety for deep slip surfaces.

The **Janbu** stability equation (Janbu, 1954; Janbu et al., 1956) is identical to Bishop except that the equation is expressed in terms of horizontal force equilibrium (see later), and a compensatory multiplying factor is introduced relating to the geometry of the slip surface (typically f_o=1.05).

$$F_f = \frac{\sum\left[\frac{\left(c'b + (W-ub)\tan\phi'\right)\sec\alpha}{(1+(1/F_f)\tan\phi'\tan\alpha)\cos\alpha}\right]}{\sum W\tan\propto} \times f_0 \qquad \text{.. (12)}$$

Horizontal Force Equilibrium

It is sometimes convenient to express the Factor of Safety in terms of horizontal force equilibrium, for example 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 cos α. Equations (3) General, (7) General with K included, (8) Greenwood with K included, (9) Simple, and (10) Swedish, may all be converted to horizontal force equilibrium in the same way as the Bishop equation (11) converts to the Janbu equation (12).

The notation F or F_m is normally used for moment equilibrium and F_F for horizontal force equilibrium.

Effects of Reinforcement, Vegetation and Hydraulic changes

The simple mathematical form of the Greenwood stability equations with the Factor of Safety simply expressed by a summation of restoring and disturbing moments or forces makes the inclusion of additional forces due to ground reinforcement, anchors or vegetation effects relatively straightforward.
It is not straightforward to add these additional forces in the Bishop, Janbu and other 'sophisticated' published solutions where the global factor of safety is applied to the shear strength parameters for each slice of the analysis resulting in some unrealistic force scenarios for the slices where anchor and reinforcement loads are applied (Krahn, 2001).

The general equation (3) is adapted for inclusion of the vegetation effects, reinforcement and hydrological changes, (Table A2, Figure A3), as follows (Greenwood et al., 2003, 2004):-

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

……... (13)

It is noted that the tangential reinforcement force, Tcosθ, is deducted from the denominator to treat it as a negative disturbing force (shear force) rather than treating it as an additional restoring force. This approach is statically correct in accordance with the force diagram. The calculated value will be identical for a value of Factor of Safety of 1.

The water forces, U_1 and U_2, acting on the downslope and upslope sides of the slice are calculated by the spreadsheet based on an assumed hydrostatic water pressure below the free water surface:-

ie, $U_1 = \frac{\gamma_w h_{w1}^2}{2}$ $\qquad \Delta U_1 = \frac{\gamma_w (h_{w1} + \Delta h_{w1})^2}{2} - \frac{\gamma_w h_{w1}^2}{2}$

Alternatively, values of U_1 and U_2 may be obtained elsewhere (by flow net or seepage program etc) and entered directly into the spreadsheet.

The additional reinforcement, vegetation and hydraulic terms are similarly added in to the Greenwood Simple (9), Greenwood (K as input) (8) and Swedish (10) equations to provide the new Factor of Safety due to the effects considered.

It is concluded that for routine stability analysis the General equation (3) is most appropriate and gives a sensible estimate of the Factor of Safety for all slope and hydrological conditions. Vegetation and reinforcement forces are readily included (13).

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List of Figures and Tables

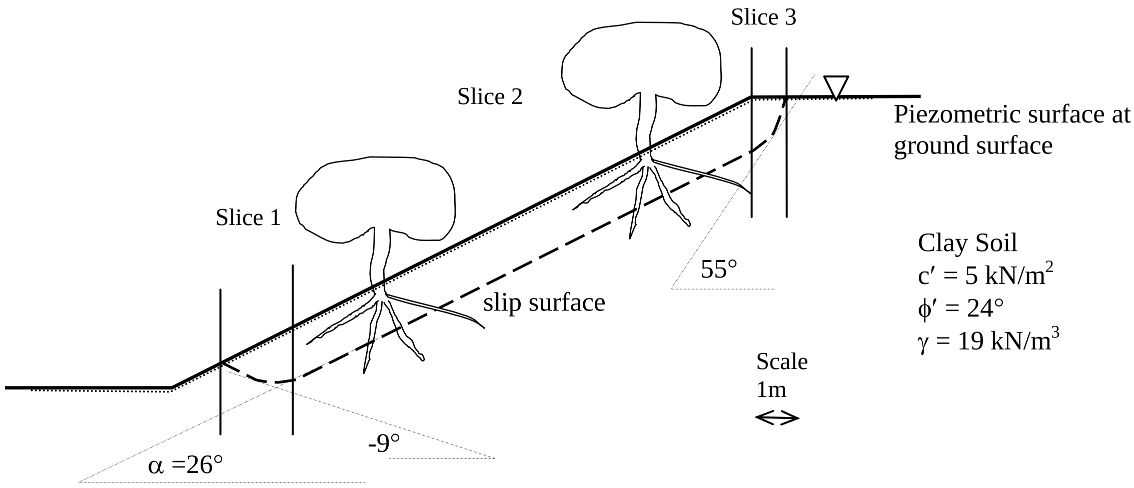

Figure 1. Scale drawing of slope and potential slip surface. Slices selected and parameters assigned.

slice	Avge height of slice Height 1 m	Unit weight of soil Unit wt 1 kN/m^3	(if other soil layers present in slice) Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	slice width, b Breadth m	base angle, α Alpha degs	Cohesion, c′ and friction angle, ϕ′, at base of slice Cohesion kN/m^2	Phi' degs	Head of water on downslope side, upslope side of slice and average h_{w1} m	h_{w2} m	h_w m	Earth press Coeff K
1	0.6	19					1.9	-9	5	24	0	1.2	0.6	0.5
2	1.2	19					9.2	26	5	24	1.2	1.2	1.2	0.5
3	0.6	19					0.75	55	5	24	1.2	0	0.6	0.5

Table 1. Slice data prepared from scale drawing ready for input to SLIP4EX spreadsheet.

SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Sept 2004) **Sheet 1 - Comparison of Methods**

(See sheet 2, for effects of reinforcement, vegetation and hydrological changes)

PROJECT Thessaloniki conference 2004 DESCRIPTION OF ANALYSIS: 1 in 2 embankment example with vegeation effects

Date:

Enter slice Data

Slice Nr	Height 1 m	Unit wt 1 kN/m^3	Height 2 m	Unit wt 2 kN/m^3	Height 3 m	Unit wt 3 kN/m^3	Breadth m	Alpha degrees	Cohesion* kN/m^2	Phi' degrees	hw1 m	hw2 m	hw m	K
1	0.6	19					1.9	-9	5	24	0	1.2	0.6	0.5
2	1.2	19					9.2	26	5	24	1.2	1.2	1.2	0.5
3	0.6	19					0.75	55	5	24	1.2	0	0.6	0.5
4													0	
5													0	
6													0	
7													0	
8													0	
9													0	
10													0	
11													0	
12													0	
13													0	
14													0	
15													0	

Calculated forces on slices

							Total Resistance - Moment equilibrium						**Total Resistance - Horizontal force equilibı**			
							General	General	Simple	Simple	Swedish	Bishop	General	General	Simple	Simple
	W	U1	U2	u	Dist force	cohesive res		K'		K'				K '		K'
slice	kN	kN	kN	kN/m2	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN	kN
1	21.66	0.00	7.20	6.00	-3.39	9.62	14.51	14.56	14.13	14.19	14.00	15.22	14.69	14.74	14.31	14.36
2	209.76	7.20	7.20	12.00	91.95	51.18	80.43	85.16	90.94	95.67	80.43	83.85	89.49	94.75	101.18	106.44
3	8.55	7.20	0.00	6.00	7.00	6.54	7.85	8.91	7.57	8.63	5.23	6.14	13.69	15.53	13.20	15.04
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
				total	**95.57**	67.34	**102.79**	**108.63**	**112.64**	**118.48**	**99.66**	105.20	**117.87**	**125.03**	**128.69**	**135.85**

Factors of Safety (no reinforcement or vegetation)	Moment equilibrium F_m	Force equilibrium F_f
Greenwood General	**1.08**	**1.06**
Greenwood General (K as input)	**1.14**	**1.13**
Greenwood Simple	**1.18**	**1.16**
Greenwood Simple (K as input)	**1.24**	**1.22**
Swedish	**1.04**	**1.02**
Bishop	1.10	
Janbu (fo =1.05)		1.13

Bishop iteration			Janbu Iteration	
F initial	F input	F calc	F input	F calc
1	1.10	1.10	1.13	1.13

Table 2. Input data and output results of SLIP4EX analysis showing calculated forces on each slice of the analysis and comparisons of Factor of Safety calculated by different methods.

	Root force	**Root direction**	**Additional cohesion**	**Change in water table**			**Mass of vegetation**	**Wind force**	**Wind direction**
	T	Theta	c'v	delta hw1	delta hw2	delta hw	Wv	D	Beta
slice	kN (/m)	deg	kN/m2	m	m	m	kN (/m)	kN (/m)	deg.
1	0.95	45		0	-0.1	-0.05	0	0	0
2	5	45		-0.1	-0.1	-0.1			
3	0.6	45		-0.1		-0.05			

Table 3. Selected parameters to reflect the contribution of vegetation assigned to each slice.

SLIP4EX - SLOPE STABILITY ANALYSIS (NTU Sept 2004)

Sheet 2 - EFFECTS OF REINFORCEMENT, VEGETATION AND HYDROLOGICAL CHANGES (See sheet 1, for Comparison of Methods)

PROJECT Thessaloniki conference 2004 DESCRIPTION OF ANALYSIS: 1 in 2 embankment example with vegeation effects
Date: 0

Reinforcement, Vegetation and Hydraulic changes
Enter effects for relevant slices

slice	T kN (/m)	Theta deg	c'v kN/m2	delta hw1 m	delta hw2 m	delta hw m	Wv kN (/m)	D kN (/m)	Beta deg.
1	0.95	45		0	-0.1	-0.05	0	0	0
2	5	45		-0.1	-0.1	-0.1			
3	0.6	45		-0.1		-0.05			
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									

Calculated Reinforcement / Vegetation / Hydraulic effects

	Additional disturbing force (to reinf. and veg.)				Additional Restoring Forces									Total additional resista	
	Veg.Weigh	reinf dist fo	Wind dist f	Total add. dist force	add cohesion	add weight	add u	add U1	add U2	add 'U2-U1	add 'U2-U1	add wind	add T	General	Simple
slice	kN	kN	kN	kN	kN	kN	kN	kN	kN	Gen kN	Simple kN	kN	kN	kN	kN
1	0.00	-0.67	0.00	-0.67	0.00	0.00	-0.43	0.00	-1.15	0.08	0.01	0.00	0.30	0.65	0.72
2	0.00	-3.54	0.00	-3.54	0.00	0.00	-4.56	-1.15	-1.15	0.00	0.88	0.00	1.57	6.13	5.26
3	0.00	-0.42	0.00	-0.42	0.00	0.00	-0.29	-1.15	0.00	0.42	0.20	0.00	0.19	0.06	0.28
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	0.00	-4.63	0.00	**-4.63**	0.00	0.00	-5.28	-2.30	-2.30	0.50	1.08	0.00	2.06	**6.84**	**6.26**

Factors of Safety with Reinforcement ,Vegetation and hydraulic changes included

		F_m
Greenwood General	No reinforcement/Veg	**1.08**
	with reinf /veg /water as input	**1.21**
Greenwood General (K as input)	No reinforcement/Veg	**1.14**
	With reinf /veg /water as input	**1.27**
Greenwood Simple	No reinforcement/veg	**1.18**
	With reinf/veg/water as input	**1.31**
Swedish	No reinforcement/veg	**1.04**
	With reinf/veg/water as input	**1.18**

Table 4. Input ‘vegetation’ data and output results of SLIP4EX analysis showing calculated ‘vegetation’ forces on each slice of the analysis and changes to the Factor of Safety calculated by different methods.

Term	Units	Description
h	m	Average height of slice
b	m	Width of slice
ℓ	m	Length (chord) along base of slice
R	m	Radius of slip circle
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, with 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 (negative at toe)
h_{w1}	m	Height of free water surface above left hand (downslope) side of slice
h_{w2}	m	Height of free water surface above right hand (upslope) side of slice
U_1	kN	Water force on left hand (downslope) side of slice (from flow net, seepage calculations or based on h_{w1})
U_2	kN	Water force on right hand (upslope) 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 conditions $h_w = (h_{w1} + h_{w2})/2$
u	kN/m^2	Average water pressure on base of slice ($= \gamma_w \times h_w$)
f_s	kN	Resultant seepage force on slice
T or τ	kN	Available shear resistance
S or S_f	kN	Shear force ('disturbing' force)
N'	kN	Effective normal force on base of slice
X_1,X_2	kN	Total vertical interslice forces
X_1',X_2'	kN	Effective vertical interslice forces
E_1,E_2	kN	Total horizontal interslice forces
E_1',E_2'	kN	Effective horizontal interslice forces
K	ratio	Earth Pressure Coefficient ($\sigma h'/\sigma v'$)
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
F	ratio	Factor of Safety (usually shear strength/ shear force on slip plane)

Table A1. Notation for slope stability analysis by the method of slices.

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 slice
θ	degrees	Angle between direction of T and base of slip surface
Dw	kN	Wind 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 above left (downslope) side of slice
Δh_{w2}	m	Increase in height of free water surface above right (upslope) side of slice
ΔU_1	kN	Increase in water force on left hand (downslope) side of slice
ΔU_2	kN	Increase in water force on right hand (upslope) 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, $= \gamma_w \times \Delta h_w$

Table A2. Notation for additional vegetation, reinforcement and hydrological effects.

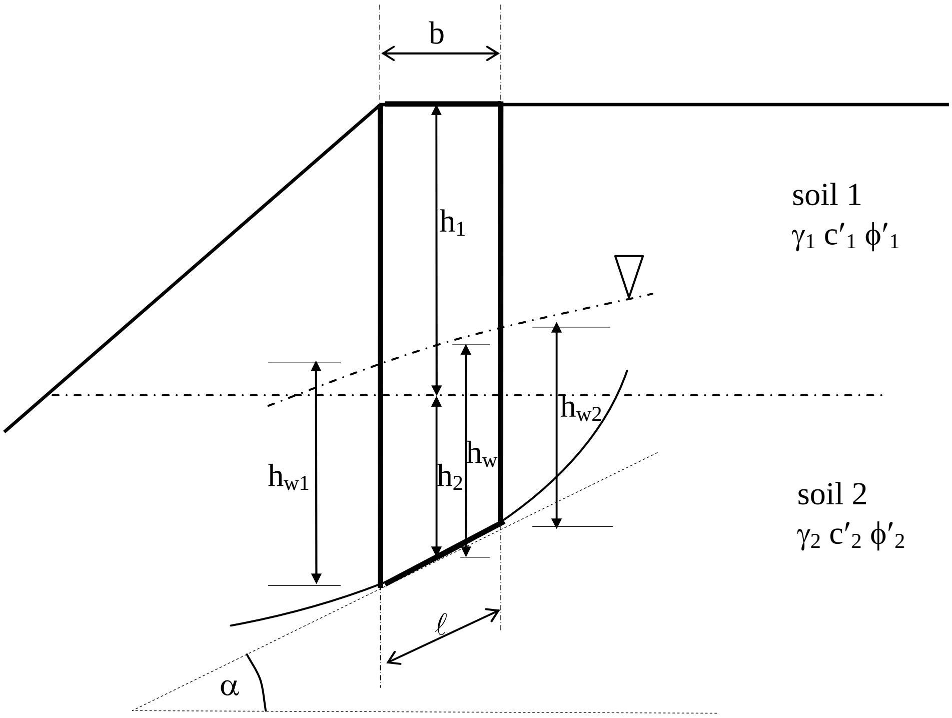

Figure A1. Limit equilibrium slope stability analysis by 'Method of Slices' - Dimensions and parameters assigned for each slice.

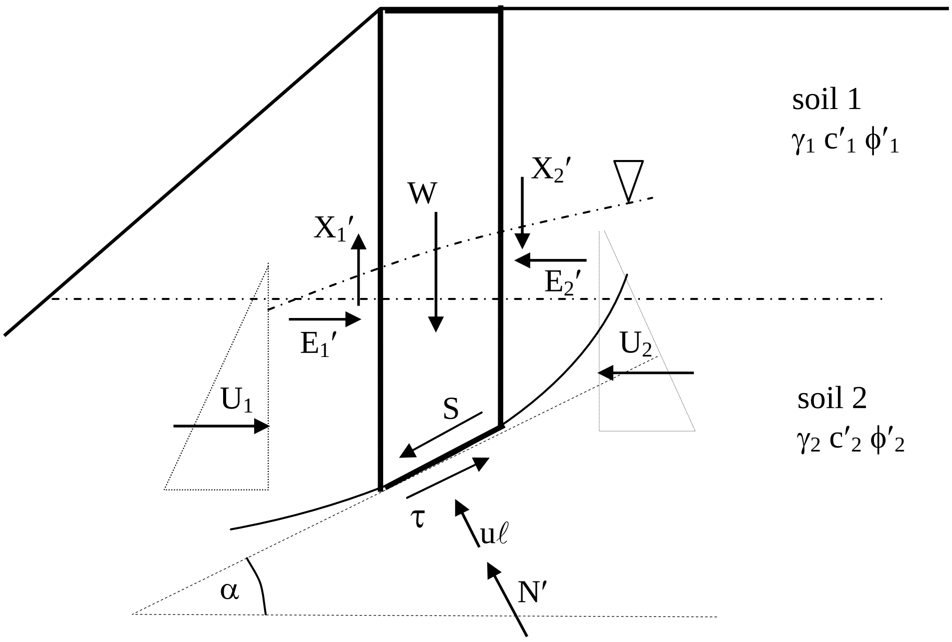

Figure A2. Forces associated with each slice.

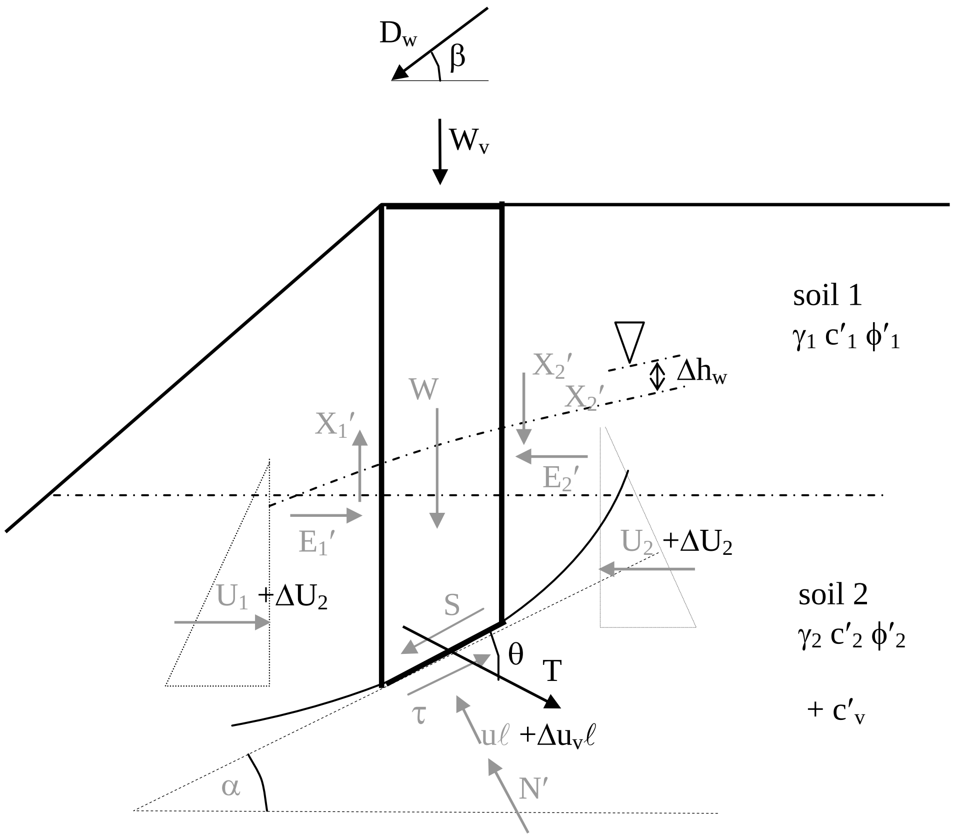

Figure A3. Additional forces due to vegetation, reinforcement and hydrological changes.