

Notice to users:

Please print this User's Guide on

**A5 paper.**

The font sizes used in this document  
will look just right at the reduced  
size.

# SLOPE

Slope Stability and Reinforced Soil  
Analysis and Design Program

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Distributed by **Geosolve**

User's Guide

Versions 12 & 12R  
for Windows 9x, ME, NT, 2000, XP

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## **1.0 INTRODUCTION**

### **1.1 SCOPE OF THE PROGRAM**

SLOPE analyses the stability of soil slopes. The program is also applicable to earth pressure and bearing capacity problems. Optional facilities are available for the analysis and design of reinforced soil. This Windows version of SLOPE is available:-

with soil reinforcement options - version 12R

without soil reinforcement options - version 12

#### **Applicability of the program to rock slopes**

Rock slopes can also be analysed if care is taken to ensure that the (wedge shaped) slip surfaces lie along joint planes or other discontinuities and that the strength parameters and water pressures reflect the conditions along these planes. Throughout the User Guide the term 'soil' is used exclusively but can be taken to include rock bearing in mind the above proviso.

#### **1.1.1 Analysis options**

The program provides a choice of methods of analysis including the following:-

Swedish Circle (or Fellenius') method

Bishop's method

Spencer's method

Janbu's method

The various methods make different assumptions about the equilibrium distribution of forces within the slipping mass. The result of each analysis is expressed as a factor of safety (FoS). In routine slope stability problems the factor of safety is calculated with respect to the strength of the soil along the slip surface. There is an option to calculate the factor of safety with respect to surcharge loads. This option is applicable to bearing capacity problems and earth pressure calculations.

#### **1.1.2 Strata profile and ground water conditions**

The ground can be described in terms of up to 25 soil strata each with different properties. In simple cases pore water pressures are calculated from the position of the water table but, in more complicated flow conditions, local values of pore pressure can be defined. Perched water tables, artesian pressures and pore pressures

due to construction can be modelled by specifying additional piezometric surfaces associated with individual strata.

### 1.1.3 Water pressures

The term 'pore pressure' in the program and in this manual refers to pore water pressure. The soil strength on the slip surface is calculated from Equation 6.1 assuming that

$$\sigma' = \sigma - u$$

where  $u = u_w$ , the pore water pressure. Pore air pressure is assumed to be negligible.

Where detailed information about the pore pressure distribution is lacking, the pore pressures in any individual stratum can be expressed as an  $r_u$  value. For fine grained soils which sustain negative pore pressures, the maximum suction can be specified. Submerged slopes can be analysed by specifying a water table above ground level.

### 1.1.4 Surcharge loads

External forces (due to buildings, strut forces in excavations etc..) can be applied to the ground surface. Earthquake forces can be modelled in a quasi-static manner by specifying horizontal and vertical acceleration factors.

### 1.1.5 Soil reinforcement

SLOPE is supplied in two versions. SLOPE version 12R includes facilities for analysing and designing reinforced soil slopes, cuttings, walls and embankments. SLOPE version 12 is only a slope stability analysis program and does not include soil reinforcement.

The stabilising effect of the reinforcement is calculated according to Department of Transport Technical Memorandum BE3/78 and BS 8006.

### Reinforcement properties data base

The interactive help in SLOPE includes a data base of reinforcement properties and partial factors of safety which are accessible interactively

### Reinforced soil design

The program can be requested to design lengths and spacings of reinforcement to achieve a specified factor of safety. The design facility makes optimum use of a range of reinforcement strengths according to the design conditions.

### **1.1.6 Slip surfaces**

Circular and non-circular slip surfaces can be analysed. A group of circular slip surfaces can be analysed by defining a rectangular grid of centres. For each centre a number of different radii can be specified. Alternatively the circles can be made to pass through a common point or touch a common tangent.

Two and three part wedges can be analysed. A group of wedges can be analysed by defining a rectangular grid of wedge nodes. For each wedge node a number of different wedges can be analysed by specifying ranges of wedge angles and toe positions.

General non-circular slip surfaces can also be analysed and may be specified individually by the user.

### **1.1.7 Units**

Data may be entered in any consistent set of units e.g. (kN, m) or (lb feet). All printout from the program is automatically annotated in the appropriate units.

## **1.2 SLOPE VERSION COMPATIBILITY**

SLOPE version 12.01 is the first Windows version of SLOPE.

SLOPE Version 12 (and 12R) have been designed to provide a high degree of compatibility with their predecessors, versions 9 and 9R at many levels:-

### **File readability**

SLOPE version 9 data files can be read and processed by Version 12.

### **Parameter definitions**

The definition and usage of all engineering parameters is preserved in version 12.

### **Two new parameters**

(i) Direction of failure during load factor calculation

When calculating factors of safety on surcharge loading you must now specify the direction of failure i.e. Left to right or Right to left. This avoids any possible ambiguity about the type of failure mechanism e.g. active or passive.

(ii) Minimum permitted enclosed angle in 2 or 3 part wedges.

This option permits the user to avoid considering implausible slip surfaces with small enclosed angles between the parts of the wedge.

### **Calculation**

The methods of calculation are identical.

### **Formatting**

The title block has been reorganised to accommodate the increased length of Filenames and Run Identifiers. The formatting of all other data and results is preserved virtually unchanged from SLOPE version 9.

### **Array sizes**

The maximum numbers of data items (strata, soil types etc...) are now as follows. The version 9 limits are shown in brackets:

max no. of strata & soil types	= 25	(9)
max no. of piezometric surfaces	= 10	(4)
max no. of layers of reinforcement	= 100	(40)
max no. of types of reinforcement	= 100	(40)
max no. of grid lines & surcharge loads	= 60	(25)

The maximum number of slices which the program may generate for the analysis is now 100. The number of slices generated is not directly controlled by the user but is a combination of the number of grid lines and surcharge loads. The increased limit gives greater flexibility to model complex problems.

To summarise, you should be able to read and process your version 9 and 9R data files and obtain virtually identical output using SLOPE version 12.

See additional notes in the SLOPE help system for users upgrading from SLOPE version 8 or earlier.

## 2.0 GETTING STARTED

Before attempting to install or execute the program you should read the README.RTF file on the master disk. This file contains important information about the program and how to install it.

### 2.1 SYSTEM REQUIREMENTS

#### 2.1.1 Memory requirements

SLOPE requires approximately 10 Mb of RAM.

#### 2.1.2 Disk Space Requirements

Disk space requirements for SLOPE version 12 are as follows:

	<b>File type</b>	<b>Disk space</b>
Program files		4 Mb
Each data file		32 kb
Output files	.OUT file	4 kb per exit/common point
	.BIN file	15 kb per exit/common point
Report files	.RTF file	20 kb
		+1 kb per exit point (text only)
		+100 kb per exit point (b/w graph)
		+2 Mb per exit point (colour graph)

You are responsible for removing old or unwanted files which will otherwise occupy valuable disk space.

#### 2.1.3 Screen and colour resolution

SLOPE requires a screen resolution of 800x600, 1024x768 or greater.

The SLOPE Graphical User Interface (GUI) which allows you to edit the data interactively will not work properly unless you enable the "True color" or "High color" palette. You can change the current Windows setting by selecting:

**Control Panel | Display | Settings | Color palette**

#### 2.1.4 Printed output

Printed output from the program is in lines up to 78 characters long. A choice of fonts and point sizes is available. Pagination of the output is designed for printing on A4 paper.

Printer options are selected at print time using a standard windows printer dialog box.

## Font selection

The default font is Courier New 9pt. Alternatives are available under the **Format | Font selection** menu

## 2.2 PROGRAM INSTALLATION

Please read the README.RTF file on the master diskette before installing.

To install the program run SETUP.EXE on Disk 1 of 2 (via the Windows **Start** button). Full instructions on installation and de-installation can be found at [www.geosolve.co.uk/faq.htm](http://www.geosolve.co.uk/faq.htm)

## 2.3 STARTING THE PROGRAM

If the installation routine has created a Geosolve program group you can click Start and select

### **Programs | Geosolve | SLOPE 12.01**

If the installation routine has created a SLOPE icon on the Windows Desktop you can double click on that. Otherwise use Windows explorer to view the SLOPE 12 folder and double click on the SLOPE.EXE application.

## 2.4 BEGINNERS GUIDE


Please read the release notes for SLOPE version 12. The following sequence of steps will familiarise you with the basic operations of SLOPE:-

### Preliminaries

1. Using Windows explorer create a folder called MyData (or other suitable name)
2. Copy the demonstration data files DEMO???.DAT from the SLOPE folder to your data folder.
3. Run SLOPE and after the opening screen press **Ctrl+O** or select **File | Open** from the main menu.
4. Use the Open file dialog box to select MyData as your current data folder
5. Select DEMO09.DAT.
6. Note the graphical display in the bottom right corner which shows the slope profile, water table and surcharges.
7. Use the "plus" and "minus" buttons in the corner of the graphic box to increase and decrease the size of the graphics box.


8. Select part of the picture for detailed viewing as follows:
  - a) Move the mouse cursor to  $X = 0, Y = 50$ .
  - b) Left click and drag down and to the right to mark a rectangular area for detailed viewing.
  - c) Release the left mouse button. The section is redrawn showing the selected area.
9. Repeat step 8 starting at different coordinates to view even more detail.
10. Restore the view of the whole section by double clicking anywhere on the plot.

### **Edit the data using the Graphical User Interface (GUI)**

11. Move the mouse cursor to a point on one of the strata. Find a point where the mouse cursor changes to a double-ended vertical arrow,  then click and drag to move the position of that stratum data point.

Observe the tabulated data display change to show the modified Strata Profile. You will have noticed that you are only able to drag profile data points within the limits of the strata above and below the stratum being edited. If you select a data point representing two or more coincident strata then all the strata are dragged together.

Note that you were only able to adjust the Y-coordinate of the selected data point. To adjust both X and Y coordinates of a data point you must hold down the Shift key while clicking and dragging.

12. Hold down the Shift key and move the mouse cursor to a point on one of the strata. Find a point where the mouse cursor changes to a pointing hand,  then click and drag to move the position of that stratum data point. Observe that you can now adjust both X and Y coordinates of the selected point. The tabulated data changes accordingly. Ground water profiles are edited in the same way.



### **Interpolation Display Mode**

13. Type **Alt+Y** to change the tabulated display of strata coordinates so that all coordinates are now displayed (Interpolation Off). Type **Alt+Y** again to revert to the partial display (Interpolation On).

#### **Interpolation On (interpolated coordinate values hidden)**

When a stratum (or ground water coordinate) is changed, all interpolated values are changed automatically so that straight line segments of the profile remain straight.

#### **Interpolation Off (all coordinate values shown)**

When a stratum (or ground water coordinate) is changed, adjacent interpolated values are left unchanged. Segments of the profile which previously were straight may now have developed local kinks.

### **More about the graphical display**

14. Observe the **hints** (yellow) which appear when the cursor is over a data item.
15. Type **Alt+C** to see the strata profile with colour shading.
16. Right click anywhere on the data plot to see the pop-up menu options.

### **Undo and Redo**

17. Type **Ctrl+Z** or click the Undo button to undo the edits one step at a time.
18. Type **Ctrl+R** to Redo the edits

### **Save, Analyse and View results**

19. Select **File | Save As** and save the data as Demo9A.dat and note the **Data last modified** time change to the current date and time.
20. Click on **Analyse** or type **Alt+A** to enter analysis mode.
21. Allow the analysis to finish normally and then view the output for successive common points by pressing **Alt+Right**. Observe the tabulated results and the graphics change as you move through the common points.
22. The factors of safety at grid points are colour coded from red (most critical) through yellow to green (safest). You can customize the colour coding by clicking on the (pale blue) Edit FoS selection options button.

23. As the cursor moves over a grid point, the local factor of safety and the coordinates are displayed bottom left of the graphics box. To view detailed results for the current grid point, right click and choose "View FoS details for Circle centre at X = , Y = "
24. Click on **Report** or type **Alt+T** to create and print a report

or alternatively (but more cumbersome)

Use the copy and paste facilities to copy data and results to a separate (Word) document:- Display the Summary results; select the tabulated text by typing **Ctrl+A**; copy it to the windows clipboard using **Ctrl+C**; paste it into the Word document. Now click on the summary graphics; copy the graphics to the windows clipboard using **Ctrl+C**; paste the graphics into the Word document.

Before going on to explore further you might like to read the General rules for data entry in Section 3.9.

### 3.0 GUIDE TO PROGRAM OPERATIONS

#### 3.1 THE SLOPE DESKTOP

Screen shots of the SLOPE Desktop in Data Input and View Results modes are shown in Figures 12a and 12b. SLOPE always runs 'maximized'. The program can be minimized but not 'normalized'. The main menu contains the following items

**File Import Edit View Format Analysis Help**

Beneath the main menu the Titles of the current data set are displayed. A yellow box in the top right corner displays the current data file name and its folder. Beneath the yellow box is the date/time stamp of the current data set i.e. the time the data was last saved to disk or edited.

In **View Results** mode (Figure 12b) a green box in the top right corner shows the number of the currently displayed exit point (wedge analysis), or common point (circular arc analysis)

The arrow buttons next to the green box are used to move backward and forward through the sequence of common points/exit points. Alternatively, click on the green selection button/indicator to see a list of common/exit points and select one for viewing.

The four Mode buttons are located under the main menu and Titles in the top left corner of the screen. The Graphics display (data or results) can be made larger or smaller using the [+] and [-] buttons in the lower right corner of the screen.

##### 3.1.1 The Graphical User Interface - GUI

The SLOPE Graphical User Interface allows you to input and edit data and manipulate the results interactively using the mouse. The GUI is discussed in the remainder of this section and also in Sections 2.1.3, 2.4, 3.12, 5.5, 9.3.1 and 15.6

##### 3.1.2 Data graphics - description

###### Grid lines

A bar at the top of the plot shows the position of the grid lines. Each grid line is represented by a vertical tick. If space permits the number of the grid line (not its x coordinate) is also shown.

###### Axes

The coordinate system is positive upwards and to the right. Axes are automatically marked at appropriate intervals.

### **Soil strata**

Soil strata are shown in solid black lines. By default soil descriptions are shown in full where space permits, otherwise only the stratum number is shown.

### **Strata shading**

By default the soil strata are not colour shaded. Choose **View | Plot options | Colour shading** or click the stripy coloured button to toggle colour shading of soil strata.

### **Surcharges**

The positions of surcharge loads are shown by red arrows. Vertical and horizontal arrows indicate the locations of the components

The lengths of the vertical arrows are an approximate indication of magnitude for small surcharges. The arrow length is roughly equal to an equivalent height of soil. Vertical arrows are limited in length to 20 mm regardless of the magnitude of the vertical surcharge.

Horizontal arrows are always 8mm long, regardless of the magnitude of the horizontal surcharge.

### **Ground water**

The water table is shown as a blue dashed line.

A local piezometric surface is plotted as a dashed (blue) line within a stratum to which it is assigned. Sections of a piezometric surface which lie outside the stratum to which it is assigned (e.g. artesian pressure profile), are plotted as dotted (blue) lines and are annotated with bracketed (blue) numbers indicating the stratum to which it is assigned.

A grid of piezometric levels is indicated by blue + signs at the grid points. When a the piezometric grid is selected for editing, the Piezometric elevations of the currently selected row of the piezometric grid are shown graphically like standpipe levels.

### **Reinforcement**

Reinforcement is indicated by red zig-zag lines. A vertical tick at the end of the reinforcement indicates an anchorage. Numbers in red at the end of the reinforcement layers indicate the reinforcement type.

### **Circular slip surface data**

The grid of circle centres is marked with black x's. The grid of centres may be omitted - right click to get the graphics pop-up menu and untick "Grid of Centres".

Common points (if specified) are marked with red **x**'s. A common tangent (if specified) is shown as a red dotted line.

### **Two and three part wedge data**

The grid of wedge nodes is marked with black **x**'s. The grid of wedge nodes may be omitted from the plot - right click to get the graphics pop-up menu and untick "Grid of wedge nodes".


Exit points are marked with red **x**'s.

### **General non-circular slip surface data**

A general non-circular slip surface is drawn in solid red lines as specified in the data.


### **Hot spots**

The display is data aware. As the mouse moves over the picture a yellow hint box appears with a description of the type of data being pointed. When the mouse is over an item which can be edited

interactively, the mouse cursor changes to a hand,  or double

headed arrow, .

### **Select part of the slope section for detailed viewing**

When the mouse cursor shows as  you may click and drag to select a part of the graphical display for detailed viewing. A dashed rectangle indicates the selected area.

It will often be necessary to view a detail in this way in order to perform interactive editing or to confirm the effect of previous edits on the geometry.

Double click anywhere on the graphical display to restore display of the whole section.

### **3.1.3 Results graphics - description**

The display changes according to the currently selected common point (circular slips) or exit point (wedges).

### **Summary graphics**

The graphical display shows the critical slip surface through each of the common points or exit points. The common points (or exit points) are numbered in red corresponding to the numbering in the tabulated results.

Factors of safety are shown at each point on the grid of centres (or wedge nodes). The factors of safety are colour coded. The value of FoS shown at each grid point is the minimum of all the slip surfaces relating to that grid point (subject to any exclusions)

### **Selected results**

The graphical display shows the critical slip surface through the currently selected common point or exit point. The common point (or exit point) is numbered in red corresponding to the numbering in the tabulated results.

Factors of safety are shown at each point on the grid of centres (or wedge nodes). The factors of safety are colour coded. The value of FoS shown at each grid point is for the slip surface relating to that grid point (subject to any exclusions).

### **View details for a particular slip surface**


1. Move the mouse over a grid point.
2. Observe the text display at the bottom left corner of the graphics box change to show the current grid coordinates and factor of safety.
3. Right click and select: "view detailed results for X= ... ,Y= ... ".

Full output for the selected slip surface will be listed on the Details/Messages page.

### **Reinforced soil design**

The graphical display shows the critical wedge through the end of each layer of reinforcement. The total required reinforcement to stabilise each wedge is shown opposite the end of the reinforcement layer.

### **Select part of the slope section for detailed viewing**

When the mouse cursor shows as  you may click and drag to select a part of the graphical display for detailed viewing. A dashed rectangle indicates the selected area.

It may be convenient to view a detail in this way in order to examine the array of factors of safety in more detail.

Double click anywhere on the graphical display to restore display of the whole section.

## Graphics in Reports

All graphical output in reports will show the currently selected detail. Make sure you have selected the appropriate section of the slope profile before creating a report.

### 3.2 THE MAIN MENU

#### 3.2.1 'File' menu

Menu item	Shortcut	Description
New Data Set		Start a new data set
Open	Ctrl+O	Open an existing file
Save	Ctrl+S	Save the current data file.
Save As		Save the current data file under a new name
-----		
PrintSetup		Select printing options
Print		
Data listing		Print current input data
Current selection - tabulated results		Print numerical output for current point/layer
Current selection - graphical results		Print graphical output for current point/layer
Report		
Review options		Review selections for printing
Print report		Print selected results of the current analysis
-----		
1.	1	List of recently opened data files
2.	2	- see Quick file open
etc. . .		
-----		
Exit	Alt+X	Terminate Slope execution
-----		

#### 3.2.2 'Edit' menu

Menu item	Shortcut	Description
New	Ctrl+N	Insert new data item
Delete	Ctrl+X	Delete data item
Copy	Ctrl+C	Copy data item to SLOPE clipboard or Copy text/graphics to Windows clipboard
Paste	Ctrl+V	Paste data item from SLOPE clipboard or Paste text/graphics from Windows clipboard
Undo	Ctrl+Z	Undo data edits
Redo	Ctrl+R	Redo data edits
-----		
Factor soil strengths	Ctrl+F	Factor soil strengths of selected soil types
Reverse coordinates	Ctrl+E	Reverse x-coordinates of all strata, loads etc...
-----		
Redundant grid lines	Ctrl+G	Remove redundant grid lines
Interpolate	Ctrl+I	Interpolate at current Y-coordinate
Interpolation Display Mode	Alt+Y	Toggle the Y-coordinate Interpolation Display Mode On or Off
-----		

### 3.2.3 'View' menu

<b>Menu item</b>	<b>Shortcut</b>	<b>Description</b>
Select Common point or Exit point or Reinforcement layer	Alt+L	Select results for one common point or one exit point or one reinforcement layer
Previous Common point or Exit point or Reinforcement layer	Alt+Left	Select results for previous common point or exit point or reinforcement layer
Next Common point or Exit point or Reinforcement layer	Alt+Right	Select results for next common point or exit point or reinforcement layer
-----		
Graphics	Alt+G	Move focus to the graphical display
Zoom Plus	Alt+Up	Increase size of graphical display
Zoom Minus	Alt+Down	Decrease size of graphical display
Half screen	Alt+V+H	Toggle the SLOPE window between full and half screen
	Alt+Z	Reduce the SLOPE window width in steps
Select detail		Click and drag to select part of the slope section for detailed viewing
Deselect detail	Double Click	Revert to showing the whole slope section
Plot Options		
Colour shading	Alt+C	Toggle display of colour shading of strata
Soil descriptions		Toggle display of soil descriptions on data plot
Grid of centres (wedge nodes)		Toggle display of grid of centres (wedge nodes)
View FoS for current grid point	Ctrl+D	Results are shown on the Messages/Details page
-----		
Data	Alt+D	Select Data input mode
Previous Data Block	Shift+Ctrl+Tab	Display previous data block for editing
Next Data Block	Ctrl+Tab	Display next data block for editing
-----		
Summary results	Alt+S	View Summary output
Selected results	Alt+R	View brief results for all slip surfaces through one common point (exit point)
Messages / Details		View messages generated during analysis or details at selected grid point
Data Listing	Alt+N	View complete data listing
-----		
View Report	Alt+T	Create and View Reports
-----		



### 3.2.4 'Format' menu

Choose **Format | Font** from the main menu or type **Alt+O** to select a new font, style or size. The new font will be applied to all subsequent analyses and their results. The new font will also be remembered the next time the program is executed. Old output files will be displayed and printed in the font prevailing at the time they were created.

To revert to the default font (Courier New, 9pt) choose **Format | Default font** from the main menu.

It is assumed that output will be printed on A4 paper and the results are paginated accordingly.

### 3.2.5 'Analysis' menu

**Analyse (Alt+A)** starts analysis of the current data. Clicking this option is equivalent to clicking the Analysis mode button.

**Interrupt analysis (Alt+I)** allows you to interrupt an analysis while it is in progress - see Section 3.3.2.

### 3.2.6 'Help' menu

There are 5 items, **Context sensitive help**, **Help Contents**, **Help Index**, **E-mail to Geosolve**, **Geosolve help line**. See Section 3.4 for details.

## 3.3 MODE BUTTONS

### 3.3.1 'Data input' mode button

Click the **Data** input mode button or select **View | Data** from the main menu or press **Alt+D** to enter Data input mode.

In Data input mode a set of 12 data edit tabs is visible. Click one of the tabs to display the associated data block e.g. Titles, Strata, Soil types etc...

Beneath the box displaying the data there is the **Data errors and warnings** box. If not all the data or errors/warnings can be displayed at once, scroll bars appear at the sides of the boxes. You can also move the splitter bar between the data and the error/warnings listings to view more or less of one box or the other.

### 3.3.2 'Analyse' mode button

Click the **Analyse** mode button to commence the analysis of the current data. Alternatively choose **Analysis | Analyse** from the main menu or type **Alt+A**. It is good practice to save newly edited data before analysing it.

On entering analysis mode the data edit display is hidden and a progress summary box appears together with a progress bar at the bottom of the screen.

The progress bar shows the number of slip surfaces analysed and the coordinates of the current circle centre or wedge node. The progress summary shows the critical factors of safety at each exit point.

At the end of the analysis the program enters **View results** mode.

### Interruption of analysis

During an analysis it may become apparent that the data is unsuitable and that time will be wasted by allowing the analysis to proceed to completion. To interrupt the analysis at any stage choose **Analysis | Interrupt Analysis** from the main menu or type **Alt+I**. After a short pause the program will display the question:-

Interrupt run?

If the response is N (no) the analysis will proceed as if nothing had happened. If the response is Y (yes) the run is interrupted and the program displays whatever results have been calculated so far.

### 3.3.3 'View Results' mode button

Click the **View Results** mode button to view the results of an analysis. The display shows 4 pages which can be viewed by clicking the tab at the top of the page, via the main menu or via a shortcut key.

Page	Shortcut	Description
Data listing	Alt+N	View a complete listing of the current data set.
Selected results	Alt+R	View selected results for the currently selected common/exit point.
Summary results	Alt+S	View summary results for all common/exit points
Messages	-	View messages generated during the analysis or details for a selected slip surface

If the data file has been edited since the results file was created then a '**Data modified**' warning is issued.

The **Selected results** box displays the results for one exit point at a time. Use the Results selection button to display results for a particular exit point. Information on these pages may be copied to the windows clipboard for use in other documents.

The display on the right hand side of the screen shows a graphical representation of the tabulated results.

### **View stored output**

To view the results of a previous analysis, read the data file from disk and then follow the procedure above for viewing results.

#### **3.3.4 'Report' mode button**

To create a report for printing or output to disk file, click the Report mode button, choose **View | Report** at the main menu or type **Alt+T**.

Details of the report options are given in Section 3.11

## **3.4 HELP FACILITIES**

### **3.4.1 Context sensitive help**

Press **F1** at any time to obtain help on the currently selected menu or data item. This help includes advice and suggestions on appropriate values for data items.

### **3.4.2 Help Contents**

Select **Help | Help contents** from the main menu to access the Contents page of the SLOPE help system.

### **3.4.3 Help Index**

Press **Alt+H** at any time to access the complete Help Index. Then click the **Find** tab of the Help Topics window and type a word or phrase to obtain Help on a topic of your choice. The help index covers most topics related to operation of the program, data input and interpretation of output.

You may browse through the complete index or a selection of the index topics. For example if you enter 'modulus' you will see a list of all index items containing the text string 'modulus'. The 'topic' need not be a complete word e.g. 'piezo' will suffice for 'piezometric'.

#### **3.4.4 Frequently Asked Questions - FAQ file**

The SLOPE FAQ file includes many useful items and is regularly updated. You can download it from [www.geosolve.co.uk/faq.htm](http://www.geosolve.co.uk/faq.htm)

#### **3.4.5 E-mail to Geosolve**

Selecting this option will cause your e-mail system (probably Outlook Express) to open up ready to send an e-mail to Geosolve. Please paste in relevant bits of SLOPE data listings or output and add a message or question.

#### **3.4.6 Geosolve help line**

For rapid assistance, or to report any quirks or bugs to Geosolve, please contact:

Daniel Borin	Tel: 0044 20 8674 7251
Geosolve	Fax: 0044 20 8674 9685
E-mail	<a href="mailto:support@geosolve.co.uk">support@geosolve.co.uk</a>
Website	<a href="http://www.geosolve.co.uk">http://www.geosolve.co.uk</a>

### 3.5 POP-UP MENUS AND HOTKEYS (SHORTCUTS)

A **right-click** of the mouse button on any part of the SLOPE desktop (Figures 12a and 12b) will display useful pop-up menus. These pop-up menus provide convenient access to many features available from the main menu or via Hot keys. Here is a summary of all the shortcut keystrokes (Hot Keys) available in SLOPE

<b>Key</b>	<b>Action</b>
F1	Context sensitive help
Ctrl+C	Copy Data / Results to clipboard
Ctrl+E	Reverse X-coordinates of all strata, surcharges, etc...
Ctrl+F	Factor soil strengths of selected soil types
Ctrl+M	View memory usage
Ctrl+N	New data item
Ctrl+O	Open file
Ctrl+P	Print
Ctrl+R	Redo
Ctrl+S	Save
Ctrl+V	Paste data item
Ctrl+X	Delete
Ctrl+Y	reserved as alternative to Ctrl+R
Ctrl+Z	Undo
Ctrl+Tab	Move focus to Next block (data or results)
Shift+Ctrl+Tab	Move focus to Previous block (data or results)
Alt+A	Analyse
Alt+C	Toggle colour shading
Alt+D	View data
Alt+E	'Edit' menu
Alt+F	'File' menu
Alt+G	View graphics
Alt+H	Help index
Alt+I	Interrupt analysis
Alt+L	Select results for a common/exit point
Alt+M	View messages or Detailed results for selected slip surface
Alt+N	View data listing
Alt+O	Select font
Alt+R	View selected results
Alt+S	View summary results
Alt+T	Enter report mode
Alt+V	'View' menu
Alt+V+H	Toggle half width desktop option
Alt+W	Swap display of Bending moments / Earth pressures
Alt+X	Exit
Alt+Y	Y coordinate Interpolation Display Mode
Alt+Z	Reduce the width of the SLOPE desktop (Alt+V+H to restore)
Alt+Left	Previous exit point (results only)
Alt+Right	Next exit point (results only)
Alt+Up	Zoom + (enlarge graphical display)
Alt+Down	Zoom - (reduce graphical display)

### 3.6 RESULTS SELECTION (Common point, exit point, reinforcement layer)

In 'View results' mode (Figure 12b) the green button in the top right corner of the SLOPE desk top shows you the number of the current common point (or exit point, or reinforcement layer) depending on the type of data. The current common point (exit point or reinforcement layer) may be selected in one of the following ways:-

- Click on the green button or type **Alt+L** and select from the dropdown menu.
- Use the hot key combinations **Alt+Left** or **Alt+Right** to move backward or forward through the list of points / layers.
- Right click anywhere and select one of the options **Alt+L**, **Alt+Left** or **Alt+Right**.

While viewing results, you may find that not all common points (exit points or reinforcement layers) are available for selection because the analysis was interrupted or there were no valid results for some points/layers. The graphical display in the bottom right corner of the screen shows the results for the current common point (exit point or reinforcement layer). At the same time the tabulated results for the current common point (exit point or reinforcement layer) are shown in the panel on the left hand side of the screen.

The slip surface shown is the critical one for the selected common point (exit point or reinforcement layer).

The summary results show the critical slip surfaces for all common points (exit points or reinforcement layers) on one plot.

### 3.7 DATA FILES

A data file contains one data set.

If several data sets containing different versions of a problem are to be stored on disk, they must be stored in files with different names. If you attempt to store a data set under an existing filename, the program will print the warning:-

C:\...\filename.dat exists. Over-write?

#### Filenames

A filename consists of any sequence of up to 45 letters or numbers. You will not normally have to type the file extension (.DAT or .OUT). The program automatically gives data and output files the appropriate

file extension. The following characters should not be included in filenames:

[ ] \ . < > ? : ; /

When you do a reinforced soil design the original data file is **preserved** and a new data file (containing the reinforcement design) is created which has the characters `_RSD` added to the filename. Thus DEMO7.DAT becomes DEMO7\_RSD.DAT.

### Data folders

When data files are accessed, the program assumes that they are stored in the current folder on the currently logged drive as displayed in the yellow panel at the top of the screen. Use the **Open** and **Save As** dialog boxes to select a new folder.

#### 3.7.1 Opening an existing data file

Choose **File | Open** from the main menu or type **Ctrl+O**. Use the dialog box to select a data file. While browsing the data files, the title and subtitle of the currently highlighted file are displayed in a box at the top of the screen to assist in selecting the correct file. If the highlighted file is not a SLOPE data file a warning is displayed.

You may use the dialog box to access data on other drives and folders. The newly selected folder becomes the current folder and the data are read into memory and become the current data set.

### Quick file open

To re-open a recently accessed data file choose **File** from the main menu and select one of the files listed.

#### 3.7.2 Starting a new data set

Choose **File | New** from the main menu. You will be prompted to save your current data if it is not already saved. The program creates a skeleton data set consisting of 1 stratum and 1 soil type. You must modify and adapt it to represent your particular slope.

Soil types may be imported from other data files by copying their properties via the SLOPE clipboard (Section 6.8.1).

On completion of data entry, the data are stored in memory and are referred to as the current data set. The new data must be stored in a disk file if they are not to be lost at the end of the session.

### **3.7.3 Saving data on disk**

Choose **File | Save** or type **Ctrl+S**. The current data are saved to the current filename. Existing data in that file will be overwritten.

#### **Saving to a new file**

Choose **File | Save As** from the main menu. Use the dialog box to enter a new filename or select an existing file which will get overwritten. Use the dialog box to select a different folder or create a new folder for saving your data. You can access data in any folder on any drive. The folder containing the selected file becomes the current data folder.

### **3.7.4 Where to store your data**

Store your data in folders set aside specially for SLOPE data. Never store your data in the SLOPE program folder. Data for different projects should be kept in separate folders to facilitate archiving and retrieval of data and results.

## **3.8 DATA STRUCTURE**

### **3.8.1 Data sets**

A data set contains all the data necessary to carry out one analysis. The data in a data set are grouped into 12 data blocks. When a data set is stored on disk it occupies one file.

When a data set is entered for the first time via the keyboard, or read from a disk file, it is stored in memory (RAM) and becomes the current data set.

### **3.8.2 Run Identifiers and data file names**

The Run ID which appears in the title block is always the same as the last data filename which was read or stored on disk. In order to maintain the correspondence between Run ID and Data filename, you should always store newly edited data before carrying out an analysis. This will enable you to trace printed output to a particular data file.

You should choose a convenient mnemonic and numbering system to identify the various data files and the corresponding analyses which are generated during a job.

### **File maintenance**

You are responsible for removing old or unwanted files which will otherwise occupy valuable disk space.



### 3.9 GENERAL RULES FOR DATA ENTRY

#### 3.9.1 Selecting a data block

Click the Data input mode button or select **View | Data** from the main menu or press **Alt+D** to enter Data input mode. In Data input mode a set of 12 data edit tabs is visible. Click one of the tabs to display the associated data block e.g. Titles, Strata, Soil types etc...

#### 3.9.2 Selecting and editing a cell

Use the mouse or keypad arrows to highlight the item to be edited. Obtain help on the currently selected item by pressing **F1** .

#### Numeric and Text data

To edit Numeric data or Text data press **Enter** or click on the item to open the item for editing. To overwrite the existing value simply start typing at the highlighted box. Conclude the data entry by pressing **Tab**, **Up arrow**, **Down arrow** or **Enter**, or by clicking on another cell.

#### Options data (e.g. yes/no, drained/undrained)

Where a data item is selected from a series of options you can:-

- Click on the option and select from the dropdown menu, or
- Press the space bar to cycle through the various options, or
- Type the initial letter of the option, Y, N etc... ( this only works where there is a choice of 2 options)

#### Insert New data item

To define a new soil type, surcharge etc..., highlight the undefined item or the position in the sequence where the new item is to be inserted and:-

- Press **Ctrl+N**, or
- Choose **Edit | New** from the main menu, or
- Right click and choose **Insert at cursor** from the pop-up menu.

The exact usage depends on the data type being added. For surcharges, piezometric surfaces and reinforcement layers you can simply move to the undefined item and press **Enter**.

**Delete data item**

To delete a soil type, surcharge etc..., highlight the item and:-

- Press **Ctrl+X**, or
- Choose **Edit | Delete** from the main menu, or
- Right click and choose **Delete at cursor** from the pop-up menu.

**3.9.3 Clipboard operations**

Groups of data can be copied and pasted via the SLOPE clipboard. The following example illustrates the procedure for soil properties but the same steps can be applied to Reinforcement properties. To copy the properties of Soil Type **i** to Soil Type **j**

1. Click the **Soil types** tab
2. Move the cursor to Soil Type **i**
3. Type **Ctrl+C** or right click within the soil properties menu and select **Copy**. This copies the properties of Soil Type **i** to the SLOPE clipboard
4. Move the cursor to Soil Type **j**
5. Type **Ctrl+V** or right click within the soil properties menu and select **Paste**. This pastes the properties of Soil Type **j** from the SLOPE clipboard

Soil types can be also copied and pasted from one data file to another via the SLOPE clipboard (see Section 6.8.1).

For windows clipboard operations on results listings and graphics see Section 3.12

**3.9.4 Undo and Redo data edits**

Data edits can be undone up to a 100 steps. Type **Ctrl+Z** or choose **Edit | Undo** from the main menu.

Edits which have been undone can be redone provided no other changes have been made in the mean time. Type **Ctrl+R** or choose **Edit | Redo** from the main menu.

### 3.9.5 Moving focus

During data input, focus is either on the main form, the current data block (left side of screen) or the Graphics box (lower right) corner of screen. In general the current data block may obscure part of the Graphics box or vice versa. Click on the visible part of either box to bring it to the front.

## 3.10 VIEWING RESULTS

Refer to Section 3.3.3 for a description of the **View Results** mode button. There are 4 tabs in View Results mode. Select the item you wish to view.

### 3.10.1 Data listing

This is a complete listing of the input data. This item can be viewed even when no analysis has been done and there are no results to view. Type **Alt+N** or choose **View | Data Listing** from the main menu.

### 3.10.2 Selected results for each common point (exit point or reinforcement layer)

This table gives brief output for all or some of the slip surfaces passing through a particular common point (exit point, or reinforcement layer). The degree of selectivity is controlled by the '**FoS selection options**' (see Section 14.0).

The output for each slip surface includes the factor of safety, slip surface coordinates, slipped mass, disturbing, and restoring forces and out of balance forces. Descriptions of the output are given in Section 15.

Use the (green) selection button to select a particular common point (or exit point) for viewing. The tabulated results are also shown in graphical form in the plot on the right side of the screen.

### 3.10.3 Summary results

Summary results show the critical factors of safety for all common points (exit points or reinforcement layers). In addition, the detailed force distribution is given for the most critical slip surface.

Descriptions of summary output are given in Section 15.4. The tabulated results are also shown graphically.

### 3.10.4 Messages / Details

These progress messages generated during the analysis are generally not of interest but may be useful in certain circumstances where a problem has been encountered.

This page is also used to display the detailed force distribution for selected slip surfaces as described in Section 3.1.3.

### 3.10.5 Formatting the output

The font size and style of the results listings can be controlled using the Format option in the main menu. Click **Format | Font selection** or type **Alt+O** to bring up the font selection box. Font selection must be done before the analysis. Results cannot be reformatted after the analysis.

The default font is Courier New 9pt.

## 3.11 CREATING AND PRINTING REPORTS

To create a report for printing or output to disk file, click the **Report** mode button, choose **View | Report** at the main menu or type **Alt+T**. The following options control the information included in the report.

To leave Report mode, click **Close**, type **Esc** or close the form. No other SLOPE processing is possible while in Report mode.

### 3.11.1 Brief output (text)

Use this option to include brief output for all or selected common points (exit points or reinforcement layers). The **FoS selection rules** as defined in the output options will limit the number of slip surfaces for which output is included.

### 3.11.2 Graphical output

All graphical output in the report will show the currently selected part of the slope profile. Make an appropriate selection (see Section 3.1.3) before entering **Report mode**

### Data graphics

Tick **Data graphics** to include a picture of the data.

### **Results graphics**

Tick **Summary graphics** to include a summary graph of the critical slip surfaces for all the common points (exit points or reinforcement layers).

Tick **Graphs for all selected exit points** to include a separate graph each of critical slip surface for each of the selected common points (exit points or reinforcement layers).

#### **3.11.3 Create report**

Click **Create report** to begin creation of the report using the options selected above. The report will be created in an RTF (Rich Text Format) file in the same folder as that in which the data and results files are stored. An RTF file can be viewed and printed using MS-Word, WordPad and many other non-Windows word processing programs.

#### **3.11.4 View report**

Click **View report** to open the report file using your default word processing package (usually MS-Word). You are free to edit the report file and add comments or other information.

To return to SLOPE, close MS-Word or click on the SLOPE icon on the Windows taskbar.

#### **3.11.5 Print report**

Click **Print report** to print the report on your default printer. To print to another printer or select non-standard printer options, use **View report** and use the print facilities in MS-Word.

### 3.12 USING THE WINDOWS CLIPBOARD

Data and results listings may be copied to the windows clipboard as follows:-

1. Select all or part of the text box. This may be done by clicking and dragging or by typing **Ctrl+A** to select all text in the box.
2. Copy the selected text to the windows clipboard using the standard keyboard shortcut, **Ctrl+C** or by choosing **Edit | Copy** on the main menu.

Graphical output may be copied to the windows clipboard as follows:-

1. Display the required graphic (data or results).
2. Click in the graphics box.
3. Copy the graphic to the windows clipboard using the standard keyboard shortcut, **Ctrl+C** or by choosing **Edit | Copy** on the main menu.
4. The graphic will be scaled to occupy a fixed area suitable for an A4 page in the destination document.

### 3.13 TERMINATING PROGRAM EXECUTION

Type **Alt+X** or choose **File | Exit SLOPE** from the main menu or close the main form. Any unsaved data will be lost.

## 4.0 TITLE BLOCK and FORCE, LENGTH UNITS

I.K.BRUNEL and PARTNERS	Sheet No.
Program: SLOPE Version 12.01 Revision A01.B01.R23	Job No. ABC/123
Licensed from GEOSOLVE	Made by : DLB
Run No. DEMO1	Date:01-04-2004
Embankment dam	Checked :
Upstream face. Reservoir full. water level = +16	
-----	
	Units: kN, m

### 4.1 TITLES

'Titles' consists of six items of information which are printed in the title block at the top of the input data and at the top of each section of output. They are:-

	<b>Maximum permitted no. of characters</b>
Main title	60
Sub-title	60
Job number	7
Engineer's initials	4
Force units	2
Length units	2
Unit weight of water	-

### 4.2 FORCE AND LENGTH UNITS

The Force units and Length units entered by the user are used by the program to prompt data entry in the correct units and also to annotate the output. The suggested style is:-

**kN, m or kg, cm or lb, ft**

Data can be entered in any consistent set of units. It is up to you to ensure that the values entered for strength, density, etc., correspond to the given units.

### 4.3 UNIT WEIGHT OF WATER

The units of unit weight of water must be the same as those used for unit weight of soil (see Section 6.5).

## **5.0 STRATA PROFILE**

### **5.1 COORDINATE SYSTEM**

A cross-section of the slope should be drawn on graph paper with equal scales in the horizontal and vertical directions. A set of x-y axes should be marked on the section with the x-axis horizontal. The x-axis should point to the right and the positive y-axis must point upwards. There is no restriction on the use of negative coordinates except that all coordinate values must lie between -10000 and +10000. It is often convenient to use O.D. levels for the y coordinates.

### **5.2 SOIL STRATA**

The section should show ground level and the boundaries between the different soil strata. The strata and the boundaries between them, are numbered from ground level downwards, as shown in Figure 1a. Thus the number of each soil stratum is the same as the number of its upper boundary, so that boundary no.1 corresponds to ground level. There is no lower boundary to the section and it is assumed that the lowermost stratum extends downwards indefinitely.

The boundaries between strata must form continuous lines across the section and may not cross each other. Where there is a wedge of soil that does not extend the full width of the section (see Figure 1b), its upper and lower boundaries merge, forming a layer ABCD of very small or zero thickness. The boundaries AB and CD are shown slightly separated in Figure 1b, but they are in fact permitted to coincide.

A lens of material (C) embedded in another material (B) as shown in Figure 2a, must be drawn with upper and lower boundaries that extend to the edge of the section as shown in Figure 2b. Thus material B is actually divided into two strata (Nos. 2 and 4) having the same properties separated by thin layers KL and MN of material C (Stratum 3).

The positions of Points K and N are arbitrary as long as they lie within material B, but for convenience they have been drawn to make KL and MN horizontal.



### 5.3 DATA GRID

The positions of the strata and the water table are defined using a grid of vertical lines as shown in Figure 3a. These grid lines are drawn at the left and right hand limits of the section and at all intermediate x coordinates where there is a change of gradient in one of the strata boundaries or the water table (and piezometric surfaces).

A vertical wall or cut is represented by a line of very steep gradient. The two adjacent grid lines (Nos. 2 and 3, Figure 3b) should have a very small but finite separation. The minimum permitted separation is 0.01 units so that coordinate values can be read correctly from the printed output which is given to two decimal places.

The grid lines are used as the basis for the division into slices for the analysis. However the program automatically subdivides the large slices appropriately and therefore only the minimum number of grid lines, necessary to define the geometry of the slope and water table, need be drawn.

### 5.4 DATA ENTRY

#### Entering a new strata profile

From the main menu select **File | New** to start a new data set. The default data set consists of a simple slope profile with one stratum and 4 grid lines . You should modify this simple profile to achieve the section you wish to model.

#### Maximum number of strata and grid lines

A maximum of 25 soil strata and 60 data grid lines is permitted. At least one stratum and 3 grid lines must be defined. The lowermost stratum is assumed to extend downwards indefinitely; there is no lower boundary to the section.

#### Coordinate sequence

New x coordinates are inserted automatically at their correct position in the sequence of grid lines. The minimum permitted separation of grid lines is 0.01 units.

For a new stratum, the y coordinate at Grid Line 1 must be entered first. After Grid Line 1, y coordinates need only be entered at grid lines where there is a change of slope in that stratum. The y coordinates at intermediate grid lines will be interpolated by the program. Press **Tab** to skip over a grid line while entering coordinates of a new stratum.

Strata may not cross one another but layers of zero thickness are permitted.

## 5.5 DATA EDITING

The program displays the current coordinate values in one of **two** ways, either:-

### Interpolation ON

Strata profile								
Grid line	1	2	3	4	5	6	7	8
X-Coord	-2.00	0.00	0.30	0.60	1.50	3.00	6.00	30.00
-----								
Stratum	Y-Coord							
1 (GL)	0.00	0.00	-	10.00	-	-	-	12.00
2	0.00	0.00	5.00	-	-	-	-	7.00
3	-0.00	-	-	-	-	-	-	0.00

### Interpolation OFF

Strata profile								
Grid line	1	2	3	4	5	6	7	8
X-Coord	-2.00	0.00	0.30	0.60	1.50	3.00	6.00	30.00
-----								
Stratum	Y-Coord							
1 (GL)	0.00	0.00	5.00	10.00	10.06	10.16	10.37	12.00
2	0.00	0.00	5.00	5.02	5.08	5.18	5.38	7.00
3	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00	0.00

Press **Alt+Y** to toggle the Interpolation Display Mode on and off. A blank cell (a dash in the above figure) indicates that the y coordinate at that position is on a straight line between the adjacent displayed values i.e. it is interpolated between them.

Special edit key strokes are:

Tab	to move one column right
Shift+Tab	to move one column left
Ctrl+Right	to move several columns right
Ctrl+Left	to move several columns left
Enter	to edit selected coordinate
Ctrl+I	to interpolate at the current y coordinate
Alt+Y	to toggle the display of interpolated y coordinates
Ctrl+N	to add a stratum or grid line (according to the current cell)
Ctrl+X	to delete a stratum or grid line (according to the current cell)
Ctrl+G	to remove redundant grid lines

### 5.5.1 Insert grid lines

In the table of coordinates move the cursor to one of the grid line coordinates and press **Ctrl+N**. Enter the value of the x coordinate of the new grid line. The new grid line will be automatically inserted at its correct position within the existing sequence of grid lines. The y coordinates of soil strata and ground water level at the new grid line position are interpolated by the program from the values at adjacent grid lines.

If the new grid line coordinate lies outside the existing section then the section will be extended with horizontal strata (and water table and piezometric surfaces).

### 5.5.2 Delete a grid line

In the table of coordinates move the cursor to the grid line coordinate to be deleted and type **Ctrl+X**. The program requests confirmation:-

Delete Grid Line No.5 at X = 1.50 ?	
<input type="button" value="OK"/>	<input type="button" value="Cancel"/>

The y coordinates of soil strata and water table at the remaining grid lines are renumbered automatically.

### 5.5.3 Edit x coordinates of grid lines

#### Interpolation ON

Strata profile								
Grid line	1	2	3	4	5	6	7	8
X-Coord	-2.00	0.00	0.30	0.60	1.50	3.00	6.00	30.00
-----								
Stratum	Y-Coord							
1 (GL)	0.00	0.00	-	10.00	-	-	-	12.00
2	0.00	0.00	5.00	-	-	-	-	7.00
3	-0.00	-	-	-	-	-	-	0.00
Interpolation is ON. Undisplayed coordinates will be adjusted automatically. Alt Y to change Interpolation mode								

In the table of coordinates move the cursor to the grid line coordinate to be edited and enter the new value. The x coordinate of a grid line may not be moved beyond its immediately neighbouring grid lines i.e. the horizontal sequence of grid lines must be maintained. The outermost grid lines may be moved outwards by any amount.

The effect of changing the x coordinate on y coordinates at this grid line (and neighbouring grid lines) depends on the current Interpolation Display Mode. The y coordinates **may be adjusted** automatically by the program as follows:-

**If interpolation is OFF:**



No change to interpolated y coordinates i.e. straight line segments will not necessarily remain straight.

**If interpolation is ON:**

Y coordinates of strata which **were** interpolated, will be adjusted so that they remain interpolated i.e. straight line segments remain straight.

**Edit x coordinates using the GUI**

Section 3.1.2 describes the grid line ticks on the graphical display. Move the cursor over one of the grid line ticks. The cursor changes

from  to . Click and drag. You cannot drag a grid line beyond its immediate neighbours. The selected grid line coordinate will be highlighted in the table of strata coordinates. Not all grid line ticks may be visible if they are too close together. To see more grid line details use the facility for viewing details of the slope profile (see Section 3.1.2).

**Effect of grid line edits on ground water profiles.**

The soil strata and water pressure profiles are linked to the same grid lines. Any change to grid line coordinates is liable to have an effect on the ground water profiles. Keep an eye on the graphical display for unwanted side effects of moving grid lines. See the topic "Combined horizontal and vertical movement" in Section 5.5.4 for a way of moving the x coordinate of an individual strata point without disturbing the existing grid lines.

**5.5.4 Edit y coordinates of soil strata**

In the table of coordinates move the cursor to the y coordinate to be edited and enter the new value. The effect on neighbouring y coordinates in the same stratum depends on the current Interpolation Display Mode. The y coordinates **may be adjusted** automatically by the program as follows:-

**If interpolation is OFF:**



Neighbouring y coordinates will not be adjusted i.e. straight line segments will not necessarily remain straight.

**If interpolation is ON:**

Neighbouring y coordinates in the same stratum will be adjusted so that straight line segments remain straight provide this does not cause them to cross neighbouring strata.

**Edit y coordinates using the GUI**

Move the cursor over one of the strata at a grid line position. The

cursor changes from  to . Click and drag. The stratum coordinate can be moved vertically only (see below for combined horizontal and vertical movement). If two or more strata are coincident they will be moved together. You cannot drag a stratum above or below its immediate neighbours. The selected stratum coordinate will be highlighted in the table of strata coordinates. To edit the fine detail of the strata select part of the slope section for detailed viewing before editing (see Section 3.1.2).

**Combined horizontal and vertical movement**

Click and drag while holding down the Shift Key. The strata coordinate can now be dragged sideways. A new grid line will be created at the final x coordinate if required. The yellow box at the bottom of the graphic prompts with the message - Press "Shift" to enable x coordinate editing.

**5.5.5 Interpolation at the current y coordinate**

Lumps and bumps in strata boundaries can be straightened out by interpolating at a particular y coordinate. Move the cursor to the bump (either in the table of coordinates or on the graphic) e.g. Point E in Figure 3c) and press **Ctrl+I**.

Interpolation will take place up to the adjacent **non-interpolated** points (C and G) as shown in Figure 3c. A complication may arise where interpolation between two points in one stratum would result in it intersecting the stratum above or below. This is illustrated in Figure 3d where interpolation at E would cause the upper stratum to intersect the lower stratum, HJKLMNP.

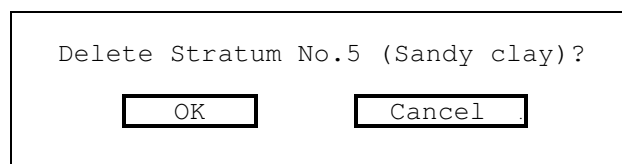
A compromise is achieved as follows: Points D and F are adjusted to lie on a straight line between C and G but Point E is lowered only as far as point M.

### 5.5.6 Insert a new stratum

To insert a new stratum **above the  $n^{\text{th}}$  stratum**, place the cursor in the table of coordinates anywhere in **the  $n^{\text{th}}$  stratum** and type **Ctrl+N**. To insert a stratum below the lowest stratum place the cursor in the bottom row of the table, marked "undefined" and type **Ctrl+N**. The y coordinate at Grid Line 1 must be entered first. After Grid Line 1, y coordinates need only be entered at grid lines where there is a change of slope in that stratum. The y coordinates at intermediate grid lines will be interpolated by the program. Press **Tab** to skip over a grid line while entering coordinates of a new stratum. Strata may not cross one another but layers of zero thickness are permitted. Out of range coordinate values will not produce an error message but will be adjusted automatically to the nearest valid value. Remember that the new y coordinates define the **upper** boundary of the new stratum. After entering the y coordinates you will still have to enter soil parameters for the new stratum.

### 5.5.7 Delete a stratum

To delete the  **$n^{\text{th}}$  stratum**, place the cursor in the table of coordinates anywhere in the  **$n^{\text{th}}$  stratum** and type **Ctrl+X**



After each deletion the strata below the deleted stratum (if any) are renumbered automatically. The soil properties of the remaining strata are also renumbered accordingly.

### 5.5.8 Reverse x coordinates

Click **Edit | Reverse coordinates** or type **Ctrl+E** to change the sign of all x coordinates values. The graphical display becomes a mirror image of itself.

## 6.0 SOIL PROPERTIES

For each stratum the following parameters are defined:-

- Stratum description
- Cohesionless or cohesive soil type
- Drained or undrained analysis
- Normally or over-Consolidated soil type
- Bulk unit weight
- Shear strength parameters
  - Friction angle
  - Cohesion or  $c_u/p'$
  - Rate of change of cohesion with depth
- Piezometric data associated with a stratum
  - Associated piezometric surface number (if required)
  - $r_u$  value (if required)
  - Maximum suction (if required)

### 6.1 STRATUM DESCRIPTION

The stratum description is a text of up to 24 characters.

### 6.2 COHESIONLESS OR COHESIVE SOIL TYPE

All soil types are defined as Cohesionless or Cohesive. The following restrictions apply:

Category	Restrictions	Typical soils
Cohesionless soil	Always "drained". Cohesion value is zero.	Sand, gravel, Cohesionless silt
Drained Cohesive soil	No restrictions	Medium/long term Behaviour of clays
Undrained Cohesive soil	$\phi = 0$	Short/medium term Behaviour of clays

### 6.3 DRAINED OR UNDRAINED SOIL TYPE

Cohesive soils are defined as behaving in either a Drained or Undrained manner. Drained and Undrained analyses are applicable as follows:-

	<b>Applicability</b>
Drained analysis	Medium / long term Behaviour
Undrained analysis	Short / medium term Behaviour

#### 6.3.1 Drained soil

The analysis of Drained cohesive soil is carried out in effective stress terms i.e. pore pressures are assumed to have time to reach equilibrium.

#### 6.3.2 Undrained soil

The analysis of Undrained cohesive soil is carried out in total stress terms - there is insufficient time for pore pressures to reach equilibrium. Soil pressures in Undrained strata are calculated in Total stress terms.

#### 6.3.3 Critical conditions for Drained and Undrained analysis.

Soft and very soft clays tend to be weakest under undrained (short term) loading and gain strength with time. Stiff and very stiff clays tend to be strong under undrained (short term) loading and lose strength as suctions dissipate with time. It is important to check behaviour under all relevant conditions. The following table gives some indication of the likely critical conditions for soft and stiff clays.

	<b>Undrained analysis (Short term)</b>	<b>Drained analysis (Long term)</b>
Soft / very soft clay	Critical	---
Stiff / very stiff clay	---	Critical



### 6.3.4 Drained and undrained cohesion

For drained cohesive soils the drained cohesion,  $c'$  must be specified. For undrained cohesive soils the undrained cohesion,  $c_u$  must be specified. See Section 6.6 for discussion of Drained and Undrained cohesion

### 6.4 NORMALLY- OR OVER-CONSOLIDATED SOIL TYPE

Undrained cohesive soil types are defined as Normally-Consolidated or Over-Consolidated (NC/OC). The Undrained Cohesion of NC cohesive soils is defined in a different way from the other types:

	Typical soil types	Cohesion model
NC cohesive	V.soft clay ( $c_u < 10$ kPa)	Strength / overburden pressure ratio, $c_u/p'$
OC cohesive	Soft/firm/stiff clay	Absolute value of $c_u$ with optional linear variation with depth

### 6.5 BULK UNIT WEIGHT

For each stratum two values of bulk unit weight must be specified:-

Above ground water level	Dry or partially saturated bulk unit weight
Below ground water level	Saturated bulk unit weight

The program automatically uses the appropriate values in the analysis according to the position of the water table. **Submerged** unit weights must **not** be specified. Water pressures on submerged slopes are taken account of automatically in the analysis.

The units of bulk unit weight must be consistent with those used for cohesion and surcharge loads:-

Cohesion Units	Corresponding units of bulk unit weight
$\text{kN/m}^2$	$\text{kN/m}^3$
$\text{kg/cm}^2$	$\text{kg/cm}^3$
$\text{lb/ft}^2$	$\text{lb/ft}^3$

### 6.6 SHEAR STRENGTH PARAMETERS

Soil strength may be described in terms of the usual  $c, \phi$  parameters, or a strength-overburden pressure ratio,  $c_u/p'$  ratio for normally consolidated cohesive soils as described in Section 6.4.

### 6.6.1 Partial factors on soil shear strength

Characteristic values of soil shear strength should be entered in the data. If a partial factor on soil strength is required (for reinforced soil or bearing capacity analysis), the partial factor is entered separately (see Section 10.4.1 and Appendix F).

### 6.6.2 $c - \phi$ parameters

The shear strength of each material is defined by two parameters, cohesion and angle of friction ( $c, \phi$ ). The available shearing resistance  $\tau_{\max}$  at each point on the slip surface is calculated by the program according to the equation:-

$$\tau_{\max} = c + \sigma' \cdot \tan \phi \quad (6.1)$$

where  $\sigma'$  is the effective stress normal to the slip surface. For drained soils (granular soils and long term failures in clay) the drained strength parameters  $c'$  and  $\phi'$  should be used as follows:-

$$\begin{aligned} c &= c' \\ \phi &= \phi' \end{aligned} \quad (6.2)$$

$\phi'$  may take any value from zero to 89 degrees.

For undrained failures in cohesive soils the undrained shear strength should be used as follows:-

$$\begin{aligned} c &= c_u \\ \phi &= 0 \end{aligned} \quad (6.3)$$

### 6.6.3 Varying shear strength within a stratum

In the above examples the strength parameters are constant within each material zone. Variations in shear strength throughout the soil mass may be described in one of three ways by defining:-

1. Material zones (strata) with different strength parameters; **or**
2. Variation of cohesion with elevation within a material zone; **or**
3. Strength-overburden pressure ratio,  $c_u/p'$  for normally consolidated cohesive soils.

**Method 2**, variation of cohesion with elevation within a material zone, is applicable to undrained failure in cohesive soils ( $\phi = 0$  analysis) in cases where the undrained cohesion varies linearly with elevation according to an equation of the form:

$$c = c_o + (y_o - y) \cdot dc/dy \quad (6.4)$$

where  $c_o$  is the undrained cohesion at an elevation (not depth)  $y = y_o$  and  $dc/dy$  is the rate of increase of cohesion with depth. It may take any value, positive or negative to represent cohesion increasing or decreasing with depth. For constant cohesion within the stratum enter a blank or zero. If a non-zero value is entered for  $dc/dy$  the program requests a value for the parameter  $y_o$  in Equation 6.4,

Datum level for given cohesion

**Method 3**, using the strength-overburden pressure ratio,  $c_u/p'$ , to define soil strength is applicable to undrained failure in normally consolidated cohesive soils where the undrained shear strength is proportional to the effective overburden pressure (Bjerrum 1973). The shear strength at a point on the slip surface is evaluated by the program by calculating the vertical effective stress (total vertical stress minus the pore pressure) and multiplying by the given value of  $c_u/p'$ :

$$\tau_{\max} = \sigma_v' \cdot c_u/p' \quad (6.5)$$

$c_u/p'$  is dimensionless and may take any value from zero to 10 although it is usually less than unity (Bjerrum 1973). No other strength information is required for the stratum.

## 6.7 PIEZOMETRIC DATA ASSOCIATED WITH A STRATUM

For strata with a non-zero value of  $\phi$ , you may define water pressure data local to that stratum. In the "Soil properties" menu select "Piezometric data associated with this stratum" and you will see the menu:

No local water pressure data Piezometric surface $r_u$ value Maximum soil suction
--

"No local water pressure data" means there is no special piezometric data associated with this stratum. The other options are dealt with in the following sections.

### 6.7.1 Local piezometric surface

Where the pore pressure regime in an individual stratum is not related to the main water table (e.g. a perched water table or artesian pressures) the stratum may be allocated its own local piezometric surface. Details of local piezometric surfaces are given in Section 7.4 .

Enter the number of the piezometric surface (up to 10 different surfaces can be defined) which describes the pore pressure profile in this stratum. The piezometric surface itself is defined in Section 7.4

### 6.7.2 $r_u$ value

In the absence of detailed information about the pore pressure distribution in a particular stratum (e.g. in the core of a dam), it may be convenient to define the pore pressures in that stratum in terms of an  $r_u$  value, which is the ratio of pore pressure to total overburden pressure (see Section 7.3).  $r_u$  may take any value between 0.001 and unity.

### 6.7.3 Soil suction

A maximum soil suction,  $H_s$  (expressed in metres head of water) may be specified. Where the slip surface lies above the water table in that stratum (see Figure 5c) the program calculates the (negative) pore pressure  $u_A$  at A on the slip surface from the equation:-

$$u_A = -\gamma_w \cdot h \quad (6.6)$$

where  $h$  is the height of the slip surface above the water table as shown by the line AB in Figure 5c. If  $h$  is greater than  $H_s$ , the negative pore pressure is assumed to be equal to  $-\gamma_w H_s$ . If no suction is specified, the program assumes zero pore pressures above the water table.

Soil suction is expressed in terms of the height of a column of water measured in the same length units as the profile coordinates. Any value between zero and 1000 units may be entered.

## 6.8 EDITING SOIL PROPERTIES

Click the "Soil properties" tab. In the table of properties move the cursor to the soil type to be edited. Press **Enter** or double-click. The program displays the menu for the selected soil stratum (soil type):-

Soil properties - Stratum 6	
Soil description (24 characters max)	Shoulder fill
Bulk Unit Weight – Above the water table	18.00 kN/m <sup>3</sup>
Bulk Unit Weight – Below the water table	21.00 kN/m <sup>3</sup>
Soil type	Cohesive
Drained / Undrained	Drained
Cohesion	10.00 kN/m <sup>2</sup>
Phi (degrees)	30.00
Rate of increase of cohesion with depth	0.00 kN/m <sup>2</sup> /m
Datum level for given cohesion	0.00
Piezometric data associated with this stratum	Piezometric surface
Piezometric surface No.	3

Select the item to be edited and enter a new value or option.

### 6.8.1 Copying soil properties

Soil properties can be copied from one soil type to another. SLOPE has its own clipboard for copying and pasting certain groups of data items e.g. Soil properties, Reinforcement properties.

Click the "Soil properties" tab. In the table of properties move the cursor to the soil type to be copied. Type **Ctrl+C**. The soil type is copied to the SLOPE clipboard (you cannot view the clipboard). Move the cursor to the destination soil type. Type **Ctrl+V**.

This facility can also be used to copy soil properties from other SLOPE data files via the following steps.

1. Save your current data file
2. Open the 'source' data file.
3. Select and copy the required soil type
4. Return to your original data file.
5. Paste the soil properties in the destination soil type.

The above steps can be repeated to copy several soil types.

## 7.0 GROUND WATER CONDITIONS

### Pore pressures on the slip surface

The program requires information about the pore pressure distribution throughout the soil mass in order to calculate the pore pressures on the slip surface. This may be done by defining:-

Item		Description
Water table	Always defined	Applies to all strata unless a grid of piezometric levels, an $r_u$ value or a piezometric surface is defined.
Local piezometric surface	Optional	Applies to the stratum for which it is defined - overrides all other pore pressure data for <b>that</b> stratum
$r_u$ value in an individual stratum	Optional	Applies to the stratum for which it is defined - overrides all other pore pressure data for <b>that</b> stratum
Grid of piezometric levels	Optional	Applies to all strata except those for which an $r_u$ value or a piezometric surface is defined.

### 7.1 WATER TABLE

The pore pressure distribution is usually defined by the position of the water table, as shown in Figure 4a. The pore pressure (expressed as the height of a column of water) at Point A on the slip surface, is assumed by the program to be equal to its depth BA below the water table. This assumption implies that the pore pressure distribution is hydrostatic and that equipotential lines are vertical. This assumption is not strictly correct as illustrated by the actual flow net. According to this the pore pressure at A is equal to AD, the vertical distance between A and C, where C is on the same equipotential as A. For most practical purposes the error is small and leads to slightly conservative estimates of the factor of safety.

### 7.2 LOCAL PIEZOMETRIC SURFACES

Perched water tables and artesian pressures may be modelled conveniently by means of "piezometric surfaces". These piezometric surfaces are defined in relation to the same grid lines used for the strata coordinates.

A piezometric surface represents the piezometric elevations which exist in a stratum where pore pressures are not controlled by the position of the main water table. Up to 10 separate piezometric surfaces may be defined, each surface representing the pore pressures in a different stratum.

In a stratum which has been allocated a local piezometric surface the pore pressures are determined by the position of the local piezometric surface instead of the main water table. The piezometric surfaces are **assigned** to particular strata under Soil Properties (Section 6.7.1).

Piezometric surfaces are optional and are always defined in **addition to the main water table which is not optional**. In strata which have **not** been allocated a piezometric surface, the program calculates pore pressures in the usual way from the position of the water table or piezometric grid.

In graphical output, the piezometric surfaces are shown in addition to the water table. A piezometric surface is shown as a dashed (blue) line within a stratum to which it is assigned. Sections of a piezometric surface which lie outside the stratum to which it is assigned (e.g. artesian pressure profile), are plotted as dotted (blue) lines and are annotated with bracketed (blue) numbers indicating the stratum to which it is assigned.

### 7.3 $r_u$ VALUES

Where an  $r_u$  value has been specified for a stratum (Section 6.7.2) the pore pressure,  $u$  on the slip surface in that stratum is calculated by the program according to the equation:-

$$u = p \cdot r_u \quad (7.1)$$

where  $p$  is total overburden pressure. An  $r_u$  value takes precedence over water table data and piezometric data when calculating pore pressures within the stratum to which the  $r_u$  value applies. The  $r_u$  value specified for one stratum does not affect the calculation of pore pressures in other strata.

#### 7.4 GRID OF PIEZOMETRIC LEVELS

The pore pressure distribution may, if necessary, be defined by **piezometric levels** at points on a rectangular grid (see Figure 4b). This method is appropriate where the equipotentials are not even approximately vertical e.g. consolidation of a clay layer between two sand layers. The grid rows and columns are defined completely independently of the grid lines used for the strata coordinates and piezometric surfaces (see Section 7.4).

The piezometric elevation  $h_A$  at grid Point A is defined as the elevation (y coordinate) of a water column which would be in equilibrium with the pore pressure at that point. The pore pressure  $u_A$  at A is given by:-

$$u_A = \gamma_w (h_A - y_A) \quad (7.2)$$

where  $y_A$  is the elevation of A and  $\gamma_w$  is the unit weight of water.

The piezometric elevation at Point K within the grid is calculated by the program by interpolating vertically and horizontally between the piezometric elevations at the four neighbouring points (A,B,C and D in Figure 4b). For a point such as L, outside the grid, the piezometric elevation is obtained by interpolating vertically between the two nearest grid points, B and E.

When a grid of piezometer levels is specified, the pore pressures on the slip surface are calculated as follows:-

**Below the water table.** Pore pressures are calculated from the data without reference to the of the water table.

**Above the water table.** Pore pressures are assumed to be **zero** unless the stratum can sustain a suction. The actual suction is calculated as described in Section 6.7.3

#### 7.5 SUBMERGED SLOPES

For a submerged slope the water table is above ground level as shown in Figure 5a. The pressure of water acting on the ground surface is automatically taken into account by the program. Pore pressures on the slip surface are calculated by the program in the usual way as in Sections 7.1 to 7.4.



The portion of the water surface, AB, outside the slope is usually horizontal corresponding to static conditions. Wave conditions can be analysed by defining a non-level water surface as shown in Figure 5b, but the results should be used with caution bearing in mind that the dynamic water pressure on the ground and on the slip surface may be different from the hydrostatic distribution assumed by the program.

## 7.6 WATER FILLED TENSION CRACKS

There is no simple way of allowing for the effect of a water filled tension crack and this can only be modelled by giving the position of the crack explicitly in the data (Figure 10a). The water level should then be set at ground level as shown and the slip surface must pass through the toe of the crack (use the common point facility – Section 9.1.3).

## 7.7 DATA ENTRY and EDITING

### 7.7.1 Unit weight of water

The units of unit weight of water must be the same as those used for unit weight of soil (see Section 6.5). Unit weight of water is defined under Titles (Section 4.3).

### 7.7.2 Ground water level and Piezometric surfaces

The coordinates of Ground water level and any Piezometric surfaces which have been defined are displayed in one table. The program displays the current coordinate values in one of **two** ways, either:-

#### Interpolation ON

Ground water level and Piezometric surfaces								
Grid line X-Coord	1	2	3	4	5	6	7	8
GW Level	-0.50	-0.50	0.00	1.00	2.40	3.00	3.50	4.00
Piezo surface 1	0.00	0.00	5.00	-	-	6.00	6.50	8.00
Piezo surface 2	-2.10	-	-	-	-	-	-	5.55
Piezo surface 3	undefined							

#### Interpolation OFF

Ground water level and Piezometric surfaces								
Grid line X-Coord	1	2	3	4	5	6	7	8
GW Level	-0.50	-0.50	0.00	1.00	2.40	3.00	3.50	4.00
Piezo surface 1	0.00	0.00	5.00	5.11	5.44	6.00	6.50	8.00
Piezo surface 2	-2.10	-1.62	-1.55	-1.48	-1.26	-0.90	-0.19	5.55
Piezo surface 3	undefined							

Press **Alt+Y** to toggle the Interpolation Display Mode on and off. A blank cell (a dash in the above figure) indicates that the y coordinate at that position is on a straight line between the adjacent displayed values i.e. it is interpolated between them.

Special edit key strokes are:

Tab	to move one column right
Shift+Tab	to move one column left
Ctrl+Right	to move several columns right
Ctrl+Left	to move several columns left
Enter	to edit selected coordinate
Ctrl+I	to interpolate at the current y coordinate
Alt+Y	to toggle the display of interpolated y coordinates
Ctrl+N	to add a stratum or grid line (according to the current cell)
Ctrl+X	to delete a stratum or grid line (according to the current cell)
Ctrl+G	to remove redundant grid lines

For a submerged slope the ground water level is simply specified as being above ground level. If there is no water table (dry ground) the y coordinates should be given large negative values below any possible slip surfaces.

To define a new Piezometric surface, move the cursor to the row to be defined and press **Enter**. The y coordinate of the Piezometric surface at Grid Line 1 must be specified first. After Grid Line 1, y coordinates need only be specified at those grid lines where there is a change of slope in the Piezometric surface.

The rules for manipulating the edit menu are similar to those for the strata profile (see Section 5.5).

### 7.7.3 Grid of piezometric levels

To edit the piezometric grid click the “Piezo grid” tab.

#### Creating a new grid

If there is no existing piezometric grid the menu displays the message.

Click here to create a piezometric grid

The program automatically creates a 4 x 4 grid in which the pore pressures are predefined as the values they would have had under the existing pore pressure data. These values should be edited to suit.

**Adding a row to the piezometric grid**

Move the cursor to the column of y coordinates and press **Ctrl+N**.

Default values of Piezometric elevation in the new Row will be obtained automatically. A choice is offered to initialise the new Row as either :

**a) Local hydrostatic values**

Obtain piezometric values from the water table (or pieometric surfaces or  $r_u$  value) as if the Piezometric grid were not present.

**b) By interpolation**

Interpolate from the existing neighbouring grid points.

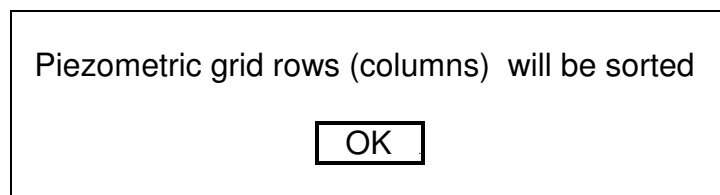
**Adding a column to the piezometric grid**

Move the cursor to the row of x coordinates and press **Ctrl+N**. Default values of Piezometric elevation in the new column will be obtained automatically. A choice is offered as above for the addition of a row of grid points.

**Editing the piezometric grid**

To edit a piezometric value, move the cursor to selected the position and enter a new value. There are no automatic interpolation rules for the piezometric grid data (unlike the Strata and Piezometric Surface data described in Section 5.5).

If you change the coordinate value of a row or column so that it lies beyond its immediate neighbours the following warning is issued:

**Delete the piezometric grid**

To delete all piezometric grid data, delete a row or column at a time until there are none left.

## 8.0 SURCHARGE LOADS APPLIED TO THE GROUND

Parts of the ground surface between specified pairs of x coordinates may be subjected to vertical and/or horizontal loads (see Figure 6a and 6b). It is assumed that the load extends indefinitely in the direction **perpendicular** to the section being analysed.

Surcharge loads							
Load No.	Loaded area from	Loaded area to	Line load or Distributed	--- Line load --- vertical kN/m run	--- Line load --- horizontal kN/m run	Equiv. distrib. Load vertical kN/m <sup>2</sup>	Equiv. distrib. Load horizontal kN/m <sup>2</sup>
1	2.00	15.00	Distributed	( 65.00)	( 0.0000)	5.000	0.0000
2	-1.00	3.00	Line	1.000	2.000	( 0.2500)	( 0.5000)

The magnitude of surcharge loads may be defined as either:

- a) **Line load** expressed as load per unit length perpendicular to the section being analysed.
- b) **Distributed load** expressed as force per **unit plan area**.

For narrow loaded areas method (a) is preferred whereas for large areas method (b) is more suitable. In the data, listing both the line loads and their equivalent distributed load values are shown. One set of values is showed bracketed to indicate that it is the **equivalent** of the entered data value (unbracketed).

### Sign convention for surcharge loads

Vertical loads are positive when acting downwards.

Horizontal loads are positive when acting in the **positive x direction**.

A maximum of 60 separate loaded areas may be defined. Inclined loads are represented by a combination of vertical and horizontal loads.

### Graphical display of surcharge loads

The positions of surcharge loads are shown by (red) arrows. The lengths of the arrows are an approximate indication of magnitude.

### Partial factors on surcharge loads

Characteristic values of surcharge loads should be entered in the data.

If a partial factor on surcharge loads is required the partial factor is entered separately (see Section 10.4.3 and Appendix F).

## 8.1 LINE LOAD

The specified line load is assumed to be distributed uniformly over the specified loaded area.

## 8.2 DISTRIBUTED LOAD

On a **horizontal** ground surface the magnitude of a distributed vertical load is equal to the normal stress on the ground surface. Similarly the magnitude of a distributed horizontal load is equal to the shear stress on a horizontal ground surface. However when the ground surface is not horizontal great care must be exercised in specifying distributed loads as illustrated in Figure 6c.

A horizontal force of 60 kN per metre run is distributed over the nearly vertical face AB. The horizontal width of the loaded area is only 0.3 m and so the equivalent distributed load to be entered in the data would be 200 kN/m<sup>2</sup>. In this case it would be better to enter the load as a line (strip) load of 60 kN per metre run.

## 8.3 FACTOR OF SAFETY ON SURCHARGE LOADS

For certain problems such as bearing capacity and earth pressure calculations, it is required to know the magnitude of the applied forces which will cause failure. In these cases the calculated factor of safety, **f**, is defined as the factor by which all the surcharge loads must be multiplied to bring the soil into a state of limiting equilibrium. See Section 10.2.2 for details of the Load Factor option.

## 8.4 ANCHOR FORCES

Anchor forces which apply a load to the ground surface, may be modelled by specifying surface line loads over a narrow strip. Inclined forces are represented by their appropriate horizontal and vertical components. It is up to the engineer to ensure that the anchors are designed with their fixed anchor length outside any possible slip surface.

## 8.5 DATA ENTRY and EDITING

To define a new surcharge load, press **Ctrl+N** at any time while the above table is displayed.

To delete a load, move the cursor to the load to be deleted and press **Ctrl+X**. The remaining loads will be renumbered automatically.

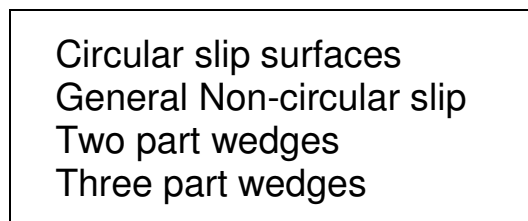
## 9.0 SLIP SURFACES

Circular and non-circular slip surfaces can be analysed. A group of circular slip surfaces is defined by a rectangular grid of centres. For each centre a number of different radii can be specified. Alternatively, the circles can be made to pass through a common point (or points) or touch a common tangent.

Two and three part wedges can be analysed. A group of wedges is defined by a rectangular grid of wedge nodes. For each wedge node a number of different wedges can be analysed by specifying ranges of wedge angles and toe positions.

General non-circular slip surfaces are specified individually by the user.

To change the type of slip surface, click on the currently selected "Slip surface type" and choose from the menu



## 9.1 CIRCULAR SLIP SURFACES

A circular slip surface is defined by the x-y coordinates of the circle centre, and the radius of the circle, defined in one of the following ways:-

- the numerical value of the radius (**not recommended**); or
- the x-y coordinates of a common point (or points) through which circles are made to pass; or
- a common tangent.

### 9.1.1 Grid of centres

A rectangular grid of centres is specified by giving the coordinates  $(x_1, y_1)$  of the corner of the grid, the grid spacing and the number of grid lines in the x and y directions, as shown in Figure 7a.

Slip surface definition	
Slip surface type	Circular slip surfaces
Corner of grid of centres, X-coordinate (m)	15.00
Y-coordinate (m)	22.00
Grid increments, X direction (m)	3.00
Y direction (m)	4.00
Number of grid lines, X-direction	6
Y-direction	7
Extended grid option required?	Yes

The grid increments must be positive and can take any value between 0.1 and 1000 units. The number of grid lines in each direction can have any value from 1 to 100.

#### Extended grid option

There is an option to let the program extend the grid of centres (at the same grid spacing) to find a minimum factor of safety. The grid is extended near the current minimum by adding whole rows and columns to the grid.

If there is more than one minimum the program may only find a local minimum. The choice of the initial grid is important in finding the overall minimum. It is recommended to carry out an initial analysis with a widely spaced grid of centres and then, having identified the critical area of the grid, to do a second analysis in that area with a finer grid.

### 9.1.2 Circles of specified radius

**Warning:** This method of specifying radii should only be used for analysing circles of known radius. It is a very inefficient method of specifying radii when trying to locate critical slip circles, and can lead to the analysis of a large number of circles which are well outside the range of interest. When trying to locate critical slip circles you are strongly advised to define the radii using the **common point** or **common tangent** method.

A range of radii may be analysed by specifying an initial radius  $R_1$  and an increment of radius  $\Delta R$  (see Figure 7a). For each centre the program then analyses circles of radius  $R_1$ ,  $R_1+\Delta R$ ,  $R_1+2\Delta R$  etc.

Slip surface definition	
Radius definition	Radius values
Radius of first circle (m)	0.00
Increments of radius (m)	0.50

Circles of small radius e.g. circles A and B, which do not intersect ground level are ignored by the program and therefore  $R_1$  may conveniently be set to zero.

For each centre the largest radius of circle which is analysed is determined by the requirement that the circle must intersect ground level at both ends within the x coordinate limits of the section. Thus for the case shown in Figure 7a the program would analyse circles C, D, and E but would stop at circle F.

If the value of  $\Delta R$  is given as zero, then for each centre the program analyses one circle of radius  $R_1$ .

### 9.1.3 Circles passing through a common point (or points)

Circles may be made to pass through a common point (or points) e.g. Points L,M,N (see Figure 7c). Thus for each centre one circle will be analysed passing through that common point.

A group of equally spaced common points e.g. Points K, L and M may be defined, such that for each centre the program analyses one circle passing through each of the common points. A group of common points is defined by the x-y coordinates of the first point, their spacing in the x and y directions and the total number of points.

Slip surface definition	
Radius definition	Common point(s)
Coordinates of (first) common point, X	20.00
Y	5.50
Number of common points	8
Increment between common points (m), X direction	1.00
Y direction	0.50



The common point method is particularly powerful in situations where the critical slip surface is expected to pass through or near:-

- The toe of a slope,
- The crest of the slope,
- The edge of a loaded area,
- The heel of a footing or embedded wall.

The common point method generally leads to better contouring of the grid of factors of safety and reduces greatly the total number of circles which need be analysed.

#### 9.1.4 Circles tangential to a common line

The common tangent may be horizontal or inclined. The two points which define the tangent may be anywhere on the tangent, not necessarily at the ends of the slope profile. There is obviously only one possible circle for each centre.

Slip surface definition		
	Radius definition	Common tangent
Common tangent: First point,	X coordinate(m)	-10.00
	Y coordinate(m)	0.50
	Second point, X coordinate(m)	117.00
	Y coordinate(m)	2.50

## 9.2 TWO- AND THREE-PART WEDGES

Two and three-part wedges (Figure 13) are defined by a wedge node,  $N$ , the wedge angle,  $\alpha$ , and the x coordinate of the toe exit point,  $x_t$ . Three-part wedges require two additional parameters, exit angle,  $\epsilon$ , and base angle,  $\beta$ .

### 9.2.1 Grid of wedge nodes

Groups of two and three-part wedges can be analysed by specifying a grid of wedge nodes and ranges of values for the other parameters. A grid of wedge nodes is a rectangular array of points defined in a similar way to the grid of circle centres.

Slip surface definition		
	Slip surface type	Two part wedges
	Automatic wedge generation	No
Corner of grid of wedge nodes,	X-coordinate (m)	13.00
	Y-coordinate (m)	5.00
Grid increments,	X direction (m)	1.00
	Y direction (m)	1.00
Number of grid lines,	X-direction	9
	Y-direction	6

### 9.2.2 Wedge angles and exit points

For each wedge node, groups of two-part wedges can be analysed by specifying ranges of values for the wedge angle,  $\alpha$ , and the x coordinate of the toe exit point,  $x_t$  as defined in Figure 13a.

#### Data for 2 part wedges

Slip surface definition		
	Slip surface type	Two part wedges
	.....	.....
Wedge angles (degrees) – First		5.00
Last		80.00
Increment		5.00
Toe exit points (X coord) – First		0.00
Last		3.50
Increment		0.50
Minimum permitted angle between wedge segments		100.00

Three-part wedges require two additional parameters, exit angle,  $\epsilon$  and base angle,  $\beta$ , as defined in Figure 13b.

#### Data for 3 part wedges

Slip surface definition		
	Slip surface type	Three part wedges
	.....	.....
Wedge angles (degrees) – First		5.00
Last		80.00
Increment		5.00
Toe exit points (X coord) – First		0.00
Last		3.50
Increment		0.50
Toe exit angles (90 = horizontal) – First		5.00
Last		1.00
Increment		1.00
Base angles (0 = horizontal) – First		-20.00
Last		20.00
Increment		2.00
Minimum permitted angle between wedge segments		100

Obviously the greater the ranges and the smaller the increments for all these parameters the more trial wedges will be analysed. The total number of wedges can become very large and time-consuming if the choice of increments is not made judiciously. As with the circular arc analysis, an initial analysis with a large coarse grid and large increments may be followed by analyses with a narrow range and finer increments.

### 9.2.3 Automatic two part wedge generation

When **soil reinforcement** has been specified, the wedge nodes can be generated automatically, based on the positions and lengths of the reinforcement. The wedges generated in this way, provide a comprehensive check on the internal and external stability of a reinforced embankment **on a firm foundation**. This facility can be used to check designs obtained with the "Design option" (Section 10.6.4) or by other methods.

#### Data for automatic two part wedge generation

Slip surface definition		
	Slip surface type	Two part wedges
	Automatic wedge generation	Yes
	Number of nodes per layer of reinforcement	4
	X-coordinate of toe of slope (m)	2.00
	Number of toe exit points per wedge node	5.00
	Wedge angles (degrees) – First	5.00
	Last	80.00
	Increment	5.00
	Minimum permitted angle between wedge segments	100.00

The wedge nodes are equally spaced along the layers of reinforcement, and the exit points are on the slope face at the ends of the layers of reinforcement. The range of wedge angles is specified manually in the usual way.

### 9.2.4 Minimum permitted enclosed angle in 2 or 3 part wedges

This option permits the user to avoid considering implausible slip surfaces with small enclosed angles between the parts of the wedge. The minimum permitted value for this parameter is 90 degrees but a value of 100 degrees is more suitable in most cases.

## 9.3 General non-circular slip surfaces

General non-circular slip surfaces are defined as a series of straight line segments between points whose x-y coordinates are given in the data (ABCD, Figure 7b). The end points must be at ground level. For the two end points (A and D), only the x coordinates are required and the program deduces their y coordinates from the previously specified ground profile. A maximum of 60 data points may be defined.

### Data for general non-circular slip surfaces

Slip surface definition		
Slip surface Point no.	X coord	Y coord
1	8.40	<i>10.80</i>
2	18.80	12.80
3	29.20	12.80
4	39.60	<i>18.00</i>
5	Undefined	
Slip type	General Non-circular slip	




The y coordinates at the end points (1 and 4, italicised) cannot be edited directly. They are determined by the ground level and will only change when you edit the corresponding x coordinates. Click on “Undefined” to add a point at the end of the list. To add a point elsewhere, highlight the insert position and type **Ctrl+N**. The x coordinates of adjacent points must differ by at least 0.01 units. To delete a point, highlight the delete position and type **Ctrl+X**.

### Change to circular slip surfaces or wedges

To delete all the General non-circular slip surface data, move the cursor to the ‘General Non-circular slip’ box. Click and select a new slip surface type.

#### 9.3.1 Edit slip surface coordinates using the GUI

Move the cursor over one of the slip surface points. The cursor

changes from  to  (or  in the case of the end-points). Click and drag. The end points can only be moved along the ground surface. You cannot drag a data point sideways beyond its immediate neighbours. The end points may be moved outwards within the overall limits of the section. The selected data point will be highlighted in the table of strata coordinates.

#### 9.3.2 Data error messages for non-circular slip surface.

A non-circular slip surface must be convex at all points and lie entirely below ground level and within the profile grid lines. Data errors are annotated thus:

- x indicates X coordinate outside section
- ^ indicates re-entrant slip surface
- \* indicates slip surface point at or above GL

“Re-entrant” means not convex.

#### **9.4 WHEN TO USE CIRCULAR OR NON-CIRCULAR SLIP SURFACES**

Most slope stability and earth pressure problems can be analysed satisfactorily assuming that the critical failure surface is circular. For example the passive failure of a wall in a frictional material is traditionally analysed using a failure surface which is a log spiral. However, the critical spiral can usually be represented by a circle which gives an almost identical factor of safety.

Reinforced soil design is automatically carried out by 2-part wedge analysis but there is no reason why you should not check reinforced soil slopes by circular arc analysis as well as the automatic wedge generation which the program offers by default. In the case of reinforced slopes on a soft foundation circular arc analysis would be an important check.

Non-circular slip surfaces are usually associated with situations where the soil strength or pore pressure conditions are highly inhomogeneous e.g. high pore pressures in a permeable stratum overlain by clay (see Figure 9a).

#### **9.5 FINDING THE CRITICAL SLIP SURFACE**

In some problems (see Figure 9b) there can be two distinct modes of failure. A typical case is that of an embankment on soft ground with stabilising berms. In this case it is important to check overall stability and also the stability of each part of the embankment. Refer to Section 9.1.2 for a discussion of the relative merits of the different ways of defining circular slip surfaces.

Care should also be taken to distinguish between a shallow surface slide in cohesionless material and more serious deep-seated slides.

## 10.0 ANALYSIS OPTIONS

'Analysis options' is a set of parameters, which control various aspects of the method of calculation. It includes partial factors which are related to the design philosophy. They are accessed by clicking on the **FoS options** tab to see the following menu:

Analysis Options	
Method of analysis	Janbu - for reinforced soil
Interslice friction/adhesion factor	0.300
Calculate FoS on	Soil Strength
Minimum no. of slices (10 suggested)	10
Partial FoS on tan(phi)	1.200
Partial FoS on drained cohesion	1.200
Partial FoS on undrained cohesion	1.500
Partial FoS on soil weight	1.000
Partial FoS on surcharge loads	1.000
Earthquake factor - Vertical	0.000
Earthquake factor - Horizontal	0.000
Reinforcement Analysis and Design	Options

Each of the options may be selected and choices made as described in the following sections. Select "Reinforcement.... Options" in order to access the options specific to Reinforcement Analysis and Design as discussed in Section 11 (only available in SLOPE version 12R).

## 10.1 METHODS OF ANALYSIS

The program offers the following choice of methods of analysis:

Swedish circle method (Fellenius)
BISHOP - Simplified : Horizontal interslice forces
JANBU - Horizontal interslice forces
BISHOP - Parallel inclined interslice forces (Spencer)
JANBU - Parallel inclined interslice forces
JANBU - for reinforced soil

### 10.1.1 Swedish Circle method (Fellenius)

This method is applicable to circular slips but may not be used for submerged slopes or where there are horizontal surcharge loads or earthquake forces.

For a  $\phi = 0$  analysis this method gives identical results to Bishop's method. However, the assumed force distribution does not satisfy conditions of overall horizontal or vertical equilibrium and so for frictional materials, calculated factors of safety usually fall below the

lower bound of solutions that satisfy statics. The errors are on the safe side but can be large (up to 60 per cent) and other methods of analysis are preferred.

### **10.1.2 Bishop's Simplified method: Horizontal interslice forces**

This method is applicable to circular slips and is recommended for all routine problems. The assumed force distribution satisfies overall vertical and moment equilibrium but not horizontal equilibrium. This leads to errors in the calculated factors of safety but these are usually insignificant and are on the safe side (Spencer 1967).

The limitations of the method have been investigated by Whitman and Bailey (1967) who conclude that it can occasionally give misleading answers. An important case is that of 'interlock' (Section 10.1.4). This arises in the case of deep slips with a low factor of safety where the toe of the slip surface passes through a frictional material. The program prints a warning message if the results are likely to be in error.

### **10.1.3 Bishop's method: Parallel inclined interslice forces (also known as Spencer's method)**

This method is applicable to circular slip surfaces. It is a refinement of Bishop's Simplified method and satisfies conditions of horizontal, vertical and moment equilibrium for the slipped mass as a whole. By assuming that all the interslice forces are parallel but not necessarily horizontal, the program calculates the inclination of the interslice forces which allows all the conditions of equilibrium to be satisfied simultaneously.

This method has been discussed by Spencer (1967) who has shown that in most cases the results differ only slightly from those obtained assuming horizontal interslice forces. The differences increase with slope angle and therefore for steep slopes this method is recommended.

Spencer's method is not immune from the 'interlock' problem mentioned in Section 10.1.4. The program prints a warning message if the calculated factor of safety is likely to be in error.

### **10.1.4 The interlock problem**

As pointed out by Bishop (1955), there is a variety of force distributions which will satisfy the conditions of equilibrium. In most

cases the assumption of horizontal or parallel inclined interslice forces is reasonable and leads to sensible results. However, in the case illustrated in Figure 8a, it is clear that such an assumption is not reasonable. The problem - known as the interlock problem - arises at the toe of the slope because of the deep slip which emerges at a steep angle  $\alpha$ , and because of the high mobilised angle of friction  $\phi'_m$ , where:-

$$\tan \phi'_m = \tan \phi' / F \quad (10.1)$$

Thus the direction of the resultant force R on the base of the slice may be almost horizontal or even pointing downwards. In order to satisfy vertical equilibrium of this slice the interslice force X must point **upwards** as shown in Figure 8b. This direction is not consistent with the assumption of either horizontal or parallel inclined interslice forces.

Slip surfaces for which this condition is liable to produce erroneous results can be identified by evaluating the expression

$$1 + \tan \alpha \cdot \tan \phi' / F$$

in the last slice at the toe of the slope. The following table gives an indication of the likely errors:

Interlock value $1 + \tan \alpha \cdot \tan \phi' / F$	Size of errors
> 0.5	Negligible
< 0.2	Significant
< 0.1	Very significant

The real contribution to stability of a frictional soil at the toe of a deep seated slip is small. Thus for practical purposes the interlock problem can be avoided without serious error by replacing the frictional property of this material with a small equivalent cohesion.

### 10.1.5 Janbu's method: Horizontal interslice forces

This method (Janbu et al. 1956) is applicable to circular and non-circular slip surfaces. The assumed force distribution satisfies overall vertical and horizontal equilibrium but not moment equilibrium. This leads to errors in the calculated factor of safety. The errors are on the safe side, but can be of the order of 15%. The errors increase according to the ratio of depth to length of the slipped mass. For



shallow slips the error is small. Janbu recommends that the calculated factor of safety be multiplied by a correction factor  $f_o$  which is related to the depth/length ratio of the slip as shown in Figure 11. The true factor of safety is calculated by multiplying the printed result,  $F_{calc}$  by a correction factor,  $f_o$

$$F_{true} = f_o \times F_{calc} \quad (10.2)$$

### **10.1.6 Janbu's method: Parallel inclined interslice forces**

This method is applicable to both circular and non-circular slip surfaces. Horizontal, vertical and moment equilibrium are satisfied for the slipped mass as a whole. When applied to circular slip surfaces the equations become identical to Spencer's method with parallel inclined interslice forces and the calculated factor of safety is the same.

The benefits and limitations of this method are similar to those of Bishop's method with parallel inclined interslice forces mentioned in Section 10.1.3. As before, the method is capable of giving misleading results due to the interlock problem. The program prints a warning message if the calculated factor of safety is likely to be in error.

### **10.1.7 Janbu's method adapted for reinforced soil**

Janbu's simplified method (horizontal interslice forces) has been modified to include an allowance for a certain amount of interslice shear. This modification has been introduced in order to achieve more economical reinforced soil designs than would be obtained assuming horizontal interslice forces. As with Janbu's simple method the basic equation satisfies horizontal and vertical equilibrium and so moment equilibrium is not guaranteed.

This method of analysis must be selected when analysing or designing reinforced soil. It is equally applicable to wedge shaped or circular slip surfaces.

The amount of interslice shear is controlled through a parameter called the 'interslice friction/adhesion factor' defined in the following paragraph.

#### **Interslice friction/adhesion factor**

Each interslice shear force is expressed as a fraction of the total horizontal force on the interslice face. It is assumed to act downwards from the up-slope side of the slice on to the down-slope side of the

slice. The value of this ratio (specified by the user) is constant throughout the slipped mass. The value is not related explicitly to either the friction angle or cohesion of the soil and is called the 'interslice friction/adhesion factor'.

Although it is theoretically possible that the calculated shear forces might exceed the available shear strength on interslice surfaces this should not happen if values within the recommended range are used.

A value of zero for the interslice friction/adhesion factor would represent a rather conservative approach, corresponding to the assumption of zero wall friction in retaining wall problems. A value of  $\frac{1}{2}$  to  $\frac{2}{3}$  would be quite usual and is reported to produce reasonably economical reinforcement designs.

### **10.1.8 Choosing a method of analysis**

For most purposes circular slips can be analysed satisfactorily using Bishop's Simplified method. If the out of balance horizontal force seems likely to cause significant errors it is recommended to locate the most critical circle using the Simplified method (for speed of computation) and then check the factor of safety for the critical circle using the method of Inclined Interslice Forces.

For two and three part wedges it is recommended to use Janbu's method with Horizontal Interslice Forces. This is the only method available in the program when soil reinforcement is specified.

For general non-circular slips it is recommended to use Janbu's method with Inclined Interslice Forces.

## **10.2 CALCULATION OF FoS ON SOIL STRENGTH OR SURCHARGE LOADS**

The program offers two different ways of calculating factors of safety.

- Calculate FoS on soil strength
- Calculate FoS on surcharge loads

"Factor of safety on soil strength" is the usual option. "Factor of safety on surcharge loads" is for assessing the critical magnitude of an applied load, either maximum or minimum.

### 10.2.1 Calculation of factors of safety on soil (and reinforcement) strength

For most problems of slope stability it is usual to calculate a factor of safety on the **shear strength of the soil**. The calculated factor of safety  $F$  is defined as the factor by which all the soil strengths (and reinforcement strengths, if applicable) must be divided to bring the soil mass into a state of limiting equilibrium. The same factor is applied simultaneously to both cohesion and  $\tan \phi'$  for all the soil strata and all reinforcement interaction and tensile strengths. Use partial factors (see below) to achieve different margins of safety on the various components of soil and reinforcement strength.

### 10.2.2 Calculation of factors of safety on applied surcharge loads

For certain problems such as bearing capacity and earth pressure calculations it is required to know the magnitude of the applied forces which will cause failure. In these cases the calculated factor of safety  $f_q$ , is defined as the factor by which all the **surcharge loads** must be multiplied to bring the soil into a state of limiting equilibrium. When this option is selected the partial factor of safety on surcharges is set to unity.

### 10.2.3 Direction of failure during Load Factor calculation

SLOPE version 12 introduces an additional parameter when calculating factors of safety on applied surcharge loads. When calculating factors of safety on surcharge loading you must specify the direction of failure i.e. Left to right or Right to left. This avoids any possible ambiguity about the type of failure mechanism e.g. active or passive.

### 10.2.4 Search for maximum or minimum load factor

When using the search (extended grid) option, the program needs to know whether to search for a **minimum** or **maximum** factor of safety on loads.

For **bearing capacity** and **passive pressure** problems, the critical load factor is the **smallest** factor which will cause failure. However, for active pressure problems the aim is to find the largest pressure on the wall and so the critical load factor is the **largest** one which causes failure. The following table summarises the use of these options:-

Type of problem	Search for
Bearing capacity or Passive limit pressure	Minimum load factor
Active limit pressure	Maximum load factor

Care must be exercised in the case of earth pressure calculations because of the two different states of limiting equilibrium - Active and Passive. The magnitude of the applied loads **specified** in the data must be somewhere near the value corresponding to the required failure condition, in order for the calculation to converge to the desired result.

For active pressure problems it is best to enter an underestimate of the applied load. For bearing capacity and passive pressure problems it is best to enter an overestimate of the critical load.

### **Partial factor of safety on soil strength during load factor calculation**

A **fixed** margin of safety with respect to **soil strength** is achieved by specifying a "Partial factor of safety on soil strength". Equilibrium is established by balancing factored loads against factored soil strengths.

### **10.3 SUBDIVISION OF SLICES FOR ANALYSIS**

The grid lines (see Section 5.3 and Figure 3) are the basis for the division into slices for the analysis. If surcharge loads are specified the program automatically inserts slice boundaries at the edges of loaded areas.

The fineness of the subdivisions is controlled by a parameter N, the 'minimum number of slices', defined by the user. For each slip surface the program makes the subdivision as follows:-

1. The program calculates the horizontal distance D between the ends of the slip surface.
2. It calculates the 'minimum slice width' d, where  $d = D/N$
3. It examines each of the slices defined by the grid lines and loaded areas and subdivides them as necessary so that the length of the base of each slice is less than d.

A value of  $N = 10$  is suitable for most circular arc problems. A value of  $N = 6$  is recommended for two part wedge analysis.

#### **10.4 PARTIAL FACTORS OF SAFETY**

Partial factors are applied to their respective parameters **before** the analysis or design starts. All factor of safety or design calculations are performed on partially factored values. The use of partial factors facilitates the achievement of balanced designs and compliance with various codes of practice.

For partial factors of safety on reinforcement properties see Section 10.6.1.

##### **10.4.1 Partial factors of safety on soil strength**

You can specify separate partial factors on the components of soil strength:

Undrained cohesion,  
Drained cohesion  
Friction.

The partial factor of safety on soil friction is applied to  $\tan \phi'$ . The different partial factors may represent varying degrees of confidence in the values of the different parameters.

Values of partial factors on (characteristic) soil strength generally lie between 1.0 and 1.5 depending on the type of strength parameters used e.g. Peak strengths, Residual strengths or Critical State strengths.

The program divides all values of cohesion and  $\tan \phi'$  by the given partial factor of safety before commencing the analysis or design.

##### **10.4.2 Partial factor of safety on soil weight**

The program applies the same factor to both bulk densities (above and below the water table). All soil densities are **multiplied** by the specified partial factor before commencing the analysis or design. A partial factor greater than unity will lead to enhanced disturbing forces but also to an increase in sliding resistance for friction soils and increased pull-out resistance for frictional reinforcement. A partial factor greater than unity will not necessarily therefore lead to a reduced value of the calculated factor of safety.

Values of partial factors on soil density should be obtained from relevant codes of practice. A cautious approach would be to try

partial factors greater and less than unity. For example if you are obliged to assume a possible 5% error in the value of soil density then you should consider partial factors of 0.95 and 1.05 on soil density.

### 10.4.3 Partial factor of safety on surcharge loads, $f_{load}$

Values of partial factors on loads should be obtained from relevant codes of practice. The program **multiplies** all surcharges, both **vertical** and **horizontal**, by the given partial factor of safety, before commencing the analysis or design.

## 10.5 MODELLING OF EARTHQUAKE LOADING

For non-earthquake conditions enter zero for both the horizontal and vertical acceleration coefficients.

Earthquake forces are modelled in a quasi-static manner by defining horizontal and vertical acceleration coefficients  $E_h$  and  $E_v$  such that the soil mass is subjected to additional horizontal and vertical accelerations  $E_h \cdot g$  and  $E_v \cdot g$  where  $g$  is the acceleration due to gravity. A positive value of horizontal acceleration is assumed to act in the direction which will decrease stability. A positive vertical acceleration acts downwards.

Applied vertical surcharge loads are assumed to be affected by the vertical component of acceleration and are increased or decreased according to whether the vertical acceleration coefficient is positive or negative (in the same way as the soil mass)

The program makes no allowance for the horizontal force on the slipped mass, due to the horizontal acceleration of **surcharge masses** which have been specified as **vertical** surcharge loads. The horizontal acceleration of surcharge masses can be modelled by either

- a) Representing the surcharges by soil strata of appropriate shape and density. This method takes care of both the vertical and horizontal accelerations of the surcharge but assumes that the surcharge is subject to the same accelerations as the soil i.e. a magnification factor of unity.

or

- b) Specifying additional horizontal surcharge loads of appropriate magnitude. Note that the horizontal surcharge load will be assumed to act at ground level whereas the force due to a real surcharge would in general act at some distance above ground level.

## 11.0 REINFORCED SOIL ANALYSIS AND DESIGN (SLOPE Version 12R only)

Horizontal layers of reinforcement can be included in the soil profile. The program is equally applicable to reinforced Slopes and reinforced soil Walls. There is no fundamental difference in the treatment of Slopes and Walls. The required degree of stability for each type of structure is achieved by the selection of appropriate partial factors of safety on soil and reinforcement strengths.

The program deals with three main types of reinforcement:

1. Sheet or grid reinforcement
2. Strip reinforcement
3. Soil nails

The stabilising effect of the reinforcement is calculated broadly in accordance with BS 8006. The stabilising force due to a layer of reinforcement is the lesser of its tensile strength and its pull-out resistance.

The program offers two modes of operation in the treatment of reinforced soil:-

### 1. Analysis mode

The program calculates factors of safety for a given slope profile, a given reinforcement arrangement and user defined slip surfaces. See Section 11.1 for details.

### 2. Design mode

The program designs the **elevations** and **lengths** of reinforcement required to achieve a given factor of safety for a given slope profile. See Section 11.2 for details.

The parameters associated with reinforced soil analysis and design are accessed by clicking on the **Reinf. design** tab on the main menu.

## 11.1 ANALYSIS MODE

In analysis mode, the user specifies the positions and strength properties of one or more layers of reinforcement and the program calculates overall factors on **soil plus reinforcement** strength.

The results are presented as a grid of factors of safety in the usual way. If the calculated factors of safety are not adequate it is up to the user to modify the slope profile or reinforcement to produce a more satisfactory arrangement.

### 11.1.1 Automatic wedge generation

When analysing reinforced slopes it is often more appropriate to consider wedge shaped slip surfaces rather than circular slip surfaces. The choice is up to the user, but your attention is drawn to the facility for **automatic** generation of two part wedges with wedge nodes at equally spaced positions along the reinforcement layers, and toe exit points at the ends of the layers. See Section 9.2.3.

## 11.2 DESIGN MODE - REINFORCED SLOPE OR EMBANKMENT ON A STABLE FOUNDATION

This option is applicable to the design of natural slopes, walls and embankments where the foundation soil is stable i.e. where there is no risk of a failure surface developing below or beyond the toe of the reinforced slope.

In design mode, you specify the position of the toe of the unstable slope, which is to be reinforced (and optionally the elevation of the bottom layer of reinforcement). The program then calculates the elevations and lengths of all the (other) layers of reinforcement required to achieve the specified overall factor of safety. Output from the program gives the elevations and lengths of all the reinforcement layers and details of the critical wedge at each reinforcement elevation.

The design covers both internal and external failure mechanisms within the slope. Stability of the foundation soil is **not** examined - failure mechanisms below the toe of the slope are **not** considered.

The design procedure decides which is the optimum type of reinforcement to use at each elevation. It makes its choice from among the reinforcement types defined in the reinforcement properties section (see Section 13). In general stronger reinforcement types will be allocated to the lower layers and weaker ones to the upper layers. An economical design will be obtained if you specify a wide range of reinforcement strengths.

You may optionally specify one layer of reinforcement in the **reinforcement geometry** section. The elevation of this layer is then assumed to be the bottom layer of reinforcement. If no layers are specified, the program will also calculate the optimum elevation of the bottom layer.



### 11.3 PARTIAL FACTORS OF SAFETY FOR REINFORCED SOIL ANALYSIS AND DESIGN

In reinforced soil analysis and design the program calculates an overall factor of safety on soil plus reinforcement strength. To ensure a balanced design it is essential to define suitable margins of stability against failure of the soil and reinforcement individually. This is achieved through partial factors of safety.

In addition to the partial factors defined in Section 10.4, the following partial factors of safety are defined for reinforced soil analysis and design:-

$f_{\text{tens}}$  = Partial factor of safety on tensile strength of reinforcement

$f_{\text{pull}}$  = Partial factor of safety on pull-out resistance

$f_{\text{slide}}$  = Partial factor of safety on direct sliding resistance

If layers of reinforcement are specified then click the **Reinf. design** tab to access these additional analysis/design options. Alternatively click on **Reinforcement Analysis and Design Options** in the **FoS options** menu.

There is no factor of safety on water pressures. To maintain a consistent approach, the water pressures should be assigned either

a) "reasonably conservative" values for the Serviceability Limit State

or

b) "worst credible" values for the Ultimate Limit State

For detailed advice on the selection of suitable partial factors please consult BS 8006 Section 7 and the interactive help in the SLOPE program.

#### 11.3.1 Partial factor of safety on tensile strength of reinforcement, $f_{\text{tens}}$

Values of partial factors on (characteristic) reinforcement strength should be obtained from relevant codes of practice. Be sure to apply a damage factor as well as a factor for the working strength. The two factors must be multiplied together as the program only accepts a single factor.

The program **divides** the values of **tensile** strength and **anchorage** strength of all reinforcements, by the given partial factor of safety, before commencing the analysis or design.

### **11.3.2 Partial factor of safety on pull-out resistance, $f_{\text{pull}}$**

Values of partial factors on soil-reinforcement interaction should be obtained from relevant codes of practice. For fabric, grid and strip reinforcement the partial factor on pull-out may be equal or similar to the partial factor on soil strength. A value of 1.3 is recommended (BS 8006, Section 7.2 Table 26) for use in conjunction with peak shear strength values on metal strip and grid reinforcement.

Higher values of  $f_{\text{pull}}$ , up to 2 to 3 may be appropriate for soil nails, due to the uncertainties of construction.

The program **divides** the values of **pull-out** resistance of all reinforcements, by the given partial factor of safety, before commencing the analysis or design.

### **11.3.3 Partial factor of safety on direct sliding resistance, $f_{\text{slide}}$**

Values of partial factors on soil-reinforcement interaction should be obtained from relevant codes of practice. For fabric, grid and strip reinforcement the partial factor on direct sliding may be equal or similar to the partial factor on soil strength. A value of 1.3 is recommended (BS 8006, Section 7.2 Table 26) for use in conjunction with peak shear strength values on metal strip and grid reinforcement.

The program **divides** the values of **direct sliding** resistance of all reinforcements, by the given partial factor of safety, before commencing the analysis or design.

### **11.3.4 Soil-reinforcement interaction limit flag**

The soil-reinforcement interaction limit flag determines how the program deals with conflicts in the data between the soil-reinforcement interaction parameters and the actual strength of the neighbouring soil. See Section 12.5.1 for details.

## 11.4 REINFORCED SOIL DESIGN PARAMETERS

The following additional parameters are required in Design mode:-

- X coordinate of toe of slope
- Reinforcement anchorage condition at slope face
- Overall design FoS on soil + reinforcement strength
- Maximum vertical spacing of reinforcement
- Minimum vertical spacing of reinforcement
- Search increment
- Reinforcement truncation option
- Minimum reinforcement length

### 11.4.1 X coordinate of toe of slope

The design takes no account of failure mechanisms which pass below or beyond the specified toe coordinate. The **y coordinate** of the toe should be at or just below the elevation of the single layer of reinforcement specified in the reinforcement data.

### 11.4.2 Reinforcement anchorage condition at slope face

All layers of reinforcement designed by the program will be designed on the assumption that they are either anchored or wrapped at the slope face.

Anchored	Specify this option for strip reinforcement and nails tied to facing panels or an anchor plate.
Wrapped	Specify this option for geogrids and other forms of sheet reinforcement which are wrapped around into the next reinforcement layer. It also includes (depending on the physical arrangement) the case of facing panels which extend up to the next layer of reinforcement.

If it is not intended to provide any anchorage at all in practice, specify "anchored" at this stage. When the design is complete, check the design by editing the reinforcement and changing all layers from "Anchored" to "No anchorage", before doing the back-analysis.

### 11.4.3 Overall design factor of safety on soil + reinforcement, $f_{des}$

This is the overall design criterion. Soil and reinforcement strengths and surcharge loads have already been partially factored (see above). The overall design factor,  $f_{des}$ , represents an additional margin of safety depending on the importance of the structure and the consequences of failure. This factor is usually unity where the

consequences of failure are not serious and 1.10 where serious damage, disruption or loss of life would be incurred. A higher value might be required where the structure is subject to an additional risk, not accounted for in the partial factors of safety.

The program examines a very large number of failure mechanisms and ensures that enough reinforcement is provided to achieve an overall factor of safety,  $f_{des}$ , on soil + reinforcement strength for all failure mechanisms. The resulting design can (and should be) back-analysed to check that the specified Overall Design FoS has been achieved as described in Section 13.5.3

#### **11.4.4 Maximum vertical spacing of reinforcement layers**

This represents the maximum practical spacing appropriate to the type of reinforcement, having regard to code requirements, the construction sequence, integrity of the slope face, the use of facing materials etc..

#### **11.4.5 Minimum vertical spacing of reinforcement layers**

This represents the minimum practical spacing possible with the particular fill material, type of reinforcement, and method of construction. The program may use a smaller vertical spacing of the reinforcement if necessary, but will issue a warning message if it does so.

#### **11.4.6 Search increment**

In calculating suitable reinforcement layer spacings, the program explores possible failure mechanisms incrementally. As a rough guide the "Search increment" should be about  $1/5$  th of the Minimum reinforcement layer spacing or about  $1/20$  th of the Maximum reinforcement layer spacing. The Search increment may not be less than  $1/2000$  th of the total slope height.

Reinforcement layer spacings will be designed by the program as multiples of the Search increment. The Maximum and minimum vertical spacing of reinforcement layers (see above) should be simple multiples of the Search increment.

### 11.4.7 Reinforcement truncation option

The design procedure calculates the **optimum** lengths and spacings of the reinforcement layers to ensure a minimum factor of safety equal to  $f_{des}$  (see above) for a very wide range of failure mechanisms. The reinforcement truncation option only affects the final presentation of the results as follows:-

<b>Parallel truncation</b>	Round up the reinforcement lengths so that the buried ends form lines parallel to the slope face.
<b>Vertical truncation</b>	Round up the reinforcement lengths so that the buried ends form vertical lines.
<b>Variable truncation</b>	Print out optimum reinforcement lengths as calculated, without adjustment.

For maximum insight into the critical failure mechanisms it is recommended to specify Variable truncation. The Parallel and Vertical truncation options may be convenient if you intend to use the computer print-out directly as the basis for design.

### 11.4.8 Minimum reinforcement length

This is an optional parameter for the user to impose a minimum reinforcement length to comply with his design code. Enter a value of zero to allow the program complete freedom to choose optimum lengths. In practice it is not usual to use lengths of reinforcement less than 2 m long and this value can reasonably be used for most designs.

## 12.0 REINFORCEMENT GEOMETRY

Details of the reinforcement geometry are accessed by clicking on the **Reinf. geometry** tab. Reinforcement geometry data is displayed as follows:

Reinforcement geometry						
Layer No.	Elev.	----- Extent ----- From X1 to X2		---- Anchorage condition --- at X1 at X2		Reinforcement type
1	15.85	12.13	12.30	Wrapped	None	2
2	14.95	11.80	12.52	Wrapped	None	2
3	14.05	11.47	12.97	Wrapped	None	2
4	13.15	11.15	13.65	Wrapped	None	3
5	12.25	10.82	13.42	Wrapped	None	3
6	11.57	10.57	13.43	Wrapped	None	1
7	10.90	10.33	13.65	Wrapped	None	1
8	10.45	10.17	13.65	Wrapped	None	1
9	10.00	10.00	13.87	Wrapped	None	1

### 12.1 REINFORCEMENT ELEVATION

The position of a layer of reinforcement is defined by its elevation and the x coordinates of the ends of the layer. You may not define more than one layer of reinforcement at the same elevation. You should also avoid excessively close spacings of reinforcement layers as this could lead to an overestimate of pull-out resistance.

Reinforcement layers may be entered in any sequence of elevations. The program automatically sorts them into vertical order.

### 12.2 REINFORCEMENT LOCATION (x direction)

The horizontal location of each layer is defined by the x coordinates of the ends of the layer. Usually one end of each layer is at the slope face but this is not a requirement. There is special help in locating the x coordinates at the slope face:-

- Move the cursor to an x coordinate in the above table
- Press **Enter** to start entering a new value
- Press **F1** to see the special help screen on x coordinates
- Select one of the suggested x coordinates:-

Select X coordinate of intersection of reinforcement with ground level

12.75

57.80

Cancel

### 12.3 REINFORCEMENT ANCHORAGE CONDITION

The input data is also used to specify whether the reinforcement is anchored at one or both ends. The actual strength of the anchorage is discussed under Reinforcement Properties (Section 13.3.2 etc.). The anchorage condition refers to the way the ends of the reinforcement are terminated. Three options are available:

<b>Anchorage type</b>	<b>Example</b>
1. Anchored	Strip reinforcement or nails attached to anchorages at the slope face.
2. Wrapped around	Sheet or grid reinforcement wrapped around into the next layer of reinforcement at the slope face. It also includes (depending on the physical arrangement) the case of facing panels which extend up to the next layer of reinforcement.
3. None	No anchorage of any kind

The buried end of the reinforcement is usually not anchored; select "None".

### 12.4 REINFORCEMENT TYPE

The reinforcement type refers to the reinforcement properties defined in Section 13. Reinforcements of several different types and/or strengths may be combined in one design.

### 13.0 REINFORCEMENT MATERIAL TYPES

Details of the reinforcement material types are accessed by clicking on the **Reinf. props.** tab. A typical table of reinforcement properties used in SLOPE is shown below:

Reinforcement properties					
Reinforce-ment type	Reinforcement material ( Description )	Tensile strength ( Anchorage ) ( strength )	Width or diam. ( Lateral ) ( spacing )	Friction coeff. Pull-out ( Direct ) ( sliding )	Adhesion (kN/m <sup>2</sup> ) ( Alpha )
1	Sheet ( Tensar SR120 )	55.00kN/m ( 55.00 )	1.000 ( 1.000 )	0.700 ( 0.700 )	5.00

Details of the parameters are described in the following sub-sections.

#### Reinforcement type

This is the number by which this type of reinforcement is referenced (allocated to a particular layer) in the reinforcement geometry.

#### Reinforcement material

The program deals with three main reinforcement materials:

1. Sheet or grid reinforcement
2. Strip reinforcement
3. Soil nails

Reinforcements of several different materials and/or strengths may be combined in one design. The properties of each type of reinforcement are defined in units suitable for that type of reinforcement.

#### Reinforcement description

This is an optional text of 16 characters where you can put the trade name and grade of the reinforcement. If a reinforcement type is selected from the data base the description and strength are automatically set.

#### Data base of reinforcement properties

The program's Help system includes a data base of various proprietary brands of reinforcement and their strength properties. They can be accessed during data entry and editing (see Section 13.6).



## Partial FoS on Reinforcement Strength

All reinforcement strength parameters defined in this section are subject to partial factors of safety, including damage factors, as describe in Section 11.3. These parameters are accessed by clicking the **Reinf. design** tab.

### Inclined reinforcement

SLOPE only models horizontal reinforcement at present. It is hoped to introduce facilities for modelling inclined reinforcement in the near future. This would be particularly relevant to soil nails.

Meanwhile you can use the program with reasonable confidence for analysing and designing soil nails with a modest angle of inclination to the horizontal in accordance with the following advice:

<b>Inclination of reinforcement to the horizontal</b>	<b>Accuracy of results Using SLOPE</b>
< 10 degrees	Excellent
10 to 20 degrees	Use with caution. Increase designed reinforcement lengths by 5%
20 to 30 degrees	Use with extreme caution
> 30 degrees	Design by other methods

### 13.1 SOIL - REINFORCEMENT INTERACTION

The interaction between reinforcement and soil can be specified in one of two ways:-

- a) Absolute values - adhesion and friction ( $c$ ,  $\mu$ )
- b) A proportion of local soil strength i.e. Interaction Coefficient

#### Absolute values

The program asks for values of adhesion and friction coefficient for Pull-out and Direct sliding failure (see Sections 13.3.4, 13.3.5 etc.. ). Remember that it would normally be unreasonable to specify adhesion and friction values greater than those of the soil adjacent to the reinforcement – but there are exceptions.

### Interaction coefficient

A simple way of ensuring a consistent and reasonable relationship between soil strength and the soil/reinforcement interaction is to specify an Interaction Coefficient (see Sections 13.3.6 etc.. ). The same coefficient is used for Pull-out and Direct sliding although different **partial factors** (see Analysis Options) can still be applied to Pull-out and Direct sliding resistance.

### 13.2 SOIL-REINFORCEMENT INTERACTION LIMIT FLAG

The soil-reinforcement interaction limit flag determines how the program deals with conflicts in the data between the soil-reinforcement interaction parameters and the actual strength of the neighbouring soil. This is important when the specified soil-reinforcement interaction parameters give rise to a higher friction or adhesion between soil and reinforcement than the friction or cohesion of the neighbouring soil.

The soil-reinforcement interaction limit flag appears as an item in the Reinforcement Analysis and Design Options menu which is accessed through either the **FoS options** tab or the **Reinf. design** tab on the main edit menu. Three strategies are available:

Option	Implementation
Strength conflict permitted	A data warning is issued <b>but</b> the full interaction strength will be used in each case.
Soil strength limit imposed	A data warning is issued and the lower friction or adhesion will be used in each case.
Strength conflict prohibited	A data error message is issued. The data will not be analysed.

The chosen option applies to **all** layers of reinforcement of all types (grids, sheets, strips and nails).

### 13.3 SHEET AND GRID REINFORCEMENT

Typical table of sheet and grid reinforcement properties.

Reinforcement properties					
Reinforce-ment type	Reinforcement material ( Description )	Tensile strength ( Anchorage ) ( strength )	Width or diam. ( Lateral ) ( spacing )	Friction coeff. Pull-out ( Direct ) ( sliding )	Adhesion (kN/m <sup>2</sup> ) ( Alpha )
1	Sheet ( Tensar SR120 )	55.00kN/m ( 55.00 )	1.000 ( 1.000 )	0.700 ( 0.700 )	5.00
2	Sheet ( ParaGrid 30/15 )	15.90kN/m ( 15.90 )	1.000 ( 1.000 )	Interaction coeff. = 0.900	

The parameters are described in detail in the following sections.

#### 13.3.1 Tensile strength - sheet/grid reinforcement

This is the tensile strength of the material as measured in laboratory tests. Characteristic or Minimum strengths may be used in conjunction with the appropriate partial factor of safety on tensile strength as described in Section 10.6.1 and in Appendix F. The Tensile strength of sheet or grid reinforcement is defined as Load per unit width e.g. kN per m run.

#### 13.3.2 Anchorage strength - sheet/grid reinforcement

Reinforcement may be anchored at one or both ends. The anchorage may, in practice, take the form of a connection to a facing panel or wrapping around into the next layer of fill. The Anchorage strength is the tensile strength of the anchored connection (if any) at the slope face or buried end.

In many cases the anchorage strength will be equal to the strength of the reinforcement but this is not necessarily so. Thus the actual anchorage strength must be specified. The Anchorage strength has the same units, and is subject to the same partial factor as the Tensile strength. The Anchorage strength is only operative for a particular layer if the anchorage condition is "Yes" (see Section 12.3).

#### 13.3.3 Reinforcement width and spacing - sheet/grid reinforcement

Reinforcement width and lateral spacing are not requested for sheet and grid reinforcement. The program automatically assigns them values of unity.

### 13.3.4 Pull-out failure - sheet/grid reinforcement

Pull-out failure occurs when the force in a piece of reinforcement exceeds the combined friction,  $\mu_{\text{avail}}$  and adhesion,  $c_{\text{avail}}$  on both faces of a sheet or grid as shown in Figure 14b. This potential failure mechanism sets an upper limit to the stabilising force provided by a layer of reinforcement. The available (factored) pull-out resistance of a reinforcement is given by:

$$P_{\text{reinf}} = 2 \cdot A_{\text{reinf}} \cdot (\sigma'_v \cdot \mu_{\text{avail}} + c_{\text{avail}}) \quad (13.1)$$

Where:

$A_{\text{reinf}}$  = Plan area of reinforcement embedded outside the slipping mass.

$\sigma'_v$  = Average vertical effective stress on the reinforcement layer

$\mu_{\text{avail}}$  = the lesser of  $\mu_{\text{pull}}/f_{\text{pull}}$  or  $\tan \phi'/f_{\text{soil}}$

$c_{\text{avail}}$  = the lesser of  $c_{\text{pull}}/f_{\text{pull}}$  or  $c/f_{\text{soil}}$

$\mu_{\text{pull}}$  = Coefficient of friction between reinforcement and soil for pull-out

$c_{\text{pull}}$  = Adhesion between reinforcement and soil for pull-out

$f_{\text{pull}}$  = Partial factor of safety on pull-out resistance

The factor, 2, takes account of the two sides of the reinforcement layer.

### 13.3.5 Direct sliding failure - sheet/grid reinforcement

Direct sliding occurs where part of the wedge shaped failure surface follows the boundary between soil and reinforcement (see Figure 14a).

The available (factored) sliding resistance  $\tau_{\text{slide}}$  is given by:

$$\tau_{\text{slide}} = \sigma'_v \cdot \mu_{\text{avail}} + c_{\text{avail}} \quad (13.2)$$

Where:

$\sigma'_v$  = Vertical effective stress on the reinforcement layer

$\mu_{\text{avail}}$  = the lesser of  $\mu_{\text{slide}}/f_{\text{slide}}$  or  $\tan \phi'/f_{\text{soil}}$

$c_{\text{avail}}$  = the lesser of  $c_{\text{slide}}/f_{\text{slide}}$  or  $c/f_{\text{soil}}$

$\mu_{\text{slide}}$  = Coefficient of friction between reinforcement and soil for direct sliding.

$c_{\text{slide}}$  =  $c_{\text{pull}}$  = Adhesion between reinforcement and soil for direct sliding and pullout.

$f_{\text{slide}}$  = Partial factor of safety on direct sliding resistance

$\phi'$  = Soil friction angle (drained)

$c$  = Soil cohesion

The pull-out friction coefficient is not necessarily equal to the direct sliding coefficient, due to the interaction of the soil particles on either side of the reinforcement. For grid reinforcement in particular it is important to use values of the pull-out coefficient obtained from pull-out tests.

### 13.3.6 Interaction coefficient - sheet/grid reinforcement

Adhesion and friction between soil and reinforcement are expressed as a proportion,  $\alpha_{int}$  of local soil strength.  $\alpha_{int}$  must be in the range zero to unity. The same coefficient is used by the program for calculating both Pull-out and Direct Sliding resistance.

The available (factored) pull-out resistance of a reinforcement is given by:

$$P_{reinf} = 2 \cdot A_{reinf} \cdot (\sigma'_v \cdot \tan \phi' + c) \cdot \alpha_{int} / f_{pull} \quad (13.3)$$

The factor, 2, takes account of the two sides of the reinforcement layer.

The available (factored) sliding resistance  $\tau_{slide}$  is given by:

$$\tau_{slide} = (\sigma'_v \cdot \tan \phi' + c) \cdot \alpha_{int} / f_{slide} \quad (13.4)$$

Where:

$A_{reinf}$  = Plan area of reinforcement embedded outside the slipping mass.

$\sigma'_v$  = Average vertical effective stress on the reinforcement layer

$c$  = Soil cohesion

$\tan \phi'$  = Soil friction

$\alpha_{int}$  = Interaction coefficient

$f_{pull}$  = Partial factor of safety on pull-out resistance

$f_{slide}$  = Partial factor of safety on direct sliding

## 13.4 STRIP REINFORCEMENT

Typical table of sheet and grid reinforcement properties.

Reinforcement properties					
Reinforce-ment type	Reinforcement material (Description)	Tensile strength (Anchorage) ( strength )	Width or diam. ( Lateral ) ( spacing )	Friction coeff. Pull-out ( Direct ) ( sliding )	Adhesion (kN/m <sup>2</sup> ) ( Alpha )
1	Strip ( Steel strip )	30.00kN ( 30.00 )	0.100 ( 0.900 )	0.500 ( 0.500 )	8.00
2	Strip (Galvanized steel)	27.00kN ( 27.00 )	0.120 ( 1.250 )	Interaction coeff. = 0.850	

The parameters are described in detail in the following sections.

#### **13.4.1 Tensile strength - strip reinforcement**

This is the tensile strength of the material as measured in laboratory tests. Characteristic or Minimum strengths may be used in conjunction with the appropriate partial factor of safety on tensile strength as described in Section 10.6.1 and in Appendix F. The Tensile strength of strip reinforcement is defined as Load per strip e.g. kN per strip.

#### **13.4.2 Anchorage strength - strip reinforcement**

The Anchorage strength is the tensile strength of the anchored connection (if any) at the slope face. Naturally, this cannot exceed the Tensile strength of a strip. The Anchorage strength has the same units, and is subject to the same partial factor as the Tensile strength. The Anchorage strength is only operative for a particular layer if the anchorage condition is "Yes" (see Section 12.3).

#### **13.4.3 Width and Lateral Spacing of strip reinforcement**

All strips are assumed to have the same width. The reinforcement spacing is measured centre to centre.

#### **13.4.4 Pull-out failure - strip reinforcement**

Pull-out failure occurs when the tension in a layer of reinforcement exceeds the combined friction,  $\mu_{\text{pull}}$  and adhesion,  $c_{\text{pull}}$  on both faces (see Figure 14b). This potential failure mechanism sets an upper limit to the stabilising force provided by a layer of reinforcement. The available (factored) pull-out resistance of strip reinforcement is given by Equation 13.1, as for sheet reinforcement. See Section 13.4.6 for pull-out resistance in terms of an Interaction Coefficient.

#### **13.4.5 Direct sliding failure - strip reinforcement**

Direct sliding occurs where part of a wedge shaped slip surface follows a (horizontal) layer of reinforcement (see Figure 14a). The available (factored) sliding resistance  $\tau_{\text{slide}}$  is given by Equation 13.2. However, for strip reinforcement, the soil/reinforcement contact forms only part of the slip surface, according to the relative width and spacing of the reinforcements. The available (factored) average sliding resistance,  $\tau_{\text{avge}}$ , on the slip surface is the weighted mean of  $\tau_{\text{slide}}$  and the soil/soil sliding resistance,  $\tau_{\text{soil}}$ ,

$$\tau_{\text{avge}} = S.\tau_{\text{slide}} + (1-S).\tau_{\text{soil}} \quad (13.5)$$

Where S is the ratio of width to spacing of the reinforcements.

The pull-out friction coefficient is not necessarily equal to the direct sliding coefficient, due to the interaction of the soil particles on either side of the reinforcement.

### 13.4.6 Interaction coefficient - strip reinforcement

Adhesion and friction between soil and reinforcement are expressed as a proportion,  $\alpha_{\text{int}}$  of local soil strength.  $\alpha_{\text{int}}$  must be in the range zero to unity. The same coefficient is used by the program for calculating both Pull-out and Direct Sliding resistance.

The available (factored) pull-out resistance of a reinforcement is given by Equation 13.3 :-

$$P_{\text{reinf}} = 2 \cdot A_{\text{reinf}} \cdot (\sigma'_v \cdot \tan \phi' + c) \cdot \alpha_{\text{int}} / f_{\text{pull}}$$

The available (factored) sliding resistance  $\tau_{\text{slide}}$  is given by Equation 13.5 :-

$$\tau_{\text{avge}} = S \cdot \tau_{\text{slide}} + (1-S) \cdot \tau_{\text{soil}}$$

and  $\tau_{\text{slide}}$  is obtained from Equation 13.4 :-

$$\tau_{\text{slide}} = (\sigma'_v \cdot \tan \phi' + c) \cdot \alpha_{\text{int}} / f_{\text{slide}}$$

All definitions are as given previously for sheet/grid reinforcement in Section 13.3.

## 13.5 SOIL NAILS

Typical parameters for nails in various soil types are given in the following Reinforcement properties tables:

### Parameters for nails in Cohesive soil

Reinforcement properties					
Reinforce-ment type	Reinforcement material ( Description )	Tensile strength ( Anchorage ) ( strength )	Width or diam. ( Lateral ) ( spacing )	Friction coeff. Pull-out ( Direct ) ( sliding )	Adhesion (kN/m <sup>2</sup> ) ( Alpha )
1	Nail (Grouted 50mm bar)	100.00kN (100.00 )	0.150 ( 1.500 )	0.000 ( 0.000 )	90.00 ( 0.50 )

### Parameters for nails in Cohesionless soil

Reinforcement properties					
Reinforce-ment type	Reinforcement material ( Description )	Tensile strength ( Anchorage ) ( strength )	Width or diam. ( Lateral ) ( spacing )	Friction coeff. Pull-out ( Direct ) ( sliding )	Adhesion (kN/m <sup>2</sup> ) ( Alpha )
1	Nail (Grouted 25mm bar)	25.00kN ( 25.00 )	0.150 ( 1.200 )	0.700 ( 0.700 )	0.00 ( 1.50 )

### Parameters for nails in mixed soils using Interaction Coefficient

Reinforcement properties					
Reinforce-ment type	Reinforcement material ( Description )	Tensile strength ( Anchorage ) ( strength )	Width or diam. ( Lateral ) ( spacing )	Friction coeff. Pull-out ( Direct ) ( sliding )	Adhesion (kN/m <sup>2</sup> ) ( A factor)
1	Nail (Driven 50mm bar )	100.00kN ( 100.00 )	0.050 ( 1.500 )	Interaction coeff. = 0.900	

For nails in purely cohesive or cohesionless soils the required parameters are described in Sections 13.5.4 and 13.5.5. For nails in mixed soils use Interaction Coefficient, see Section 13.5.7.

#### 13.5.1 Tensile strength - soil nails

This is the tensile strength of the material as measured in laboratory tests. Characteristic or Minimum strengths may be used in conjunction with the appropriate partial factor of safety on tensile strength as described in Section 10.6.1 and Appendix F. The Tensile strength of soil nails is defined as Load per nail e.g. kN per nail.



### 13.5.2 Anchorage strength - soil nails

The Anchorage strength is the tensile strength of the anchored connection (if any) at the slope face. Naturally, this cannot exceed the Tensile strength of a nail. The Anchorage strength has the same units, and is subject to the same partial factor as the Tensile strength. The Anchorage strength is only operative for a particular layer if the anchorage condition is "Yes" (see Section 12.3).

### 13.5.3 Diameter and Lateral Spacing of soil nails

The nail spacing is measured centre to centre. The diameter and spacing of the soil nails are requested.

### 13.5.4 Pull-out failure - nails in cohesionless soil

Pull-out failure occurs when the tension in a row of nails exceeds the friction,  $\mu_{\text{nail}}$ , on the perimeter of the nails (see Figure 14b). This potential failure mechanism sets an upper limit to the stabilising force provided by a row of nails. The available (factored) pull-out resistance of a nail is given by:

$$P_{\text{nail}} = \pi \cdot D_{\text{nail}} \cdot L_{\text{nail}} \cdot \sigma'_v \cdot \mu_{\text{nail}} \cdot A_{\text{nail}} / f_{\text{pull}} \quad (13.6)$$

Where:

$D_{\text{nail}}$  = Nail diameter

$L_{\text{nail}}$  = Length of nail embedded outside the slipping mass.

$\sigma'_v$  = Vertical effective stress at the nail elevation

$\mu_{\text{nail}}$  = Coefficient of friction between nail and soil

$A_{\text{nail}}$  = Empirical design factor defined in BS 8081 (Ground Anchors) as "Ratio of contact pressure between soil/nail interface to average effective overburden pressure"

$f_{\text{pull}}$  = Partial factor of safety on pull-out resistance

The program requests values of  $\mu_{\text{nail}}$  and  $A_{\text{nail}}$ .  $\mu_{\text{nail}}$  is usually equal to  $\tan \phi'$  of the surrounding soil. Values of  $A_{\text{nail}}$  have been found in practice to be not less than unity and even with tremmie grouting, values of 1.5 are commonly used for design.

### 13.5.5 Pull-out failure - nails in cohesive soil

Pull-out failure occurs when the tension in a row of nails exceeds the adhesion,  $c_{\text{nail}}$ , on the perimeter of the nails (see Figure 14b). This

potential failure mechanism sets an upper limit to the stabilising force provided by a row of nails. The available (factored) pull-out resistance of a nail is given by:

$$P_{\text{nail}} = \pi \cdot D_{\text{nail}} \cdot L_{\text{nail}} \cdot c_{\text{nail}} \cdot \alpha_{\text{nail}} / f_{\text{pull}} \quad (13.7)$$

Where:

$D_{\text{nail}}$  = Nail diameter

$L_{\text{nail}}$  = Length of nail embedded outside the slipping mass.

$c_{\text{nail}}$  = Undrained cohesion of the soil in which the nail is installed

$\alpha_{\text{nail}}$  = Adhesion factor as defined in BS 8081 (Ground Anchors)

$f_{\text{pull}}$  = Partial factor of safety on pull-out resistance

The program requests values of  $c_{\text{nail}}$  and  $\alpha_{\text{nail}}$ .  $c_{\text{nail}}$  is usually equal to peak undrained shear strength of the surrounding soil. Values of  $\alpha_{\text{nail}}$  for stiff clays have been found in practice to be between 0.3 and 0.35.

### 13.5.6 Direct sliding failure - soil nails

The program uses the nail pull-out parameters for estimating direct sliding resistance. A separate value of  $\mu_{\text{slide}}$  is not requested.

### 13.5.7 Interaction coefficient - soil nails

Adhesion and friction between soil and reinforcement are expressed as a proportion,  $\alpha_{\text{int}}$  of local soil strength.  $\alpha_{\text{int}}$  must be in the range zero to unity. The same coefficient is used by the program for calculating both Pull-out and Direct Sliding resistance.

The available (factored) pull-out resistance of a reinforcement is given by:

$$P_{\text{nail}} = \pi \cdot D_{\text{nail}} \cdot L_{\text{nail}} \cdot \alpha_{\text{int}} (\sigma'_v \cdot \tan \phi' + c) / f_{\text{pull}} \quad (13.8)$$

The available (factored) sliding resistance  $\tau_{\text{slide}}$  is given by Equation 13.5:-

$$\tau_{\text{avge}} = S \cdot \tau_{\text{slide}} + (1-S) \cdot \tau_{\text{soil}}$$

and  $\tau_{\text{slide}}$  is obtained from Equation 13.4 :-

$$\tau_{\text{slide}} = (\sigma'_v \cdot \tan \phi' + c) \cdot \alpha_{\text{int}} / f_{\text{slide}}$$

All definitions are as given previously for sheet/grid reinforcement.

### 13.6 EDITING REINFORCEMENT DATA

In order to edit the reinforcement properties data, click on the **Reinf. props.** tab. From the table of reinforcement types select one for editing and click on it or press **Enter**. The edit menu will vary according to the type of reinforcement (Sheet, Strip or Nail) and also the method of defining soil-reinforcement interaction. The following edit menus are typical:-

Reinforcement properties ... Reinforcement Type 1	
Reinforcement material	Sheet or grid
Reinforcement description (16 characters max)	Tensar 120RE
Tensile strength (kN/m run)	55.00
Anchorage strength (kN/m run)	55.00
Reinforcement width (m)	1.00
Lateral spacing of Reinforcements (m)	1.00
Soil-reinforcement interaction options	Absolute values of $\mu, c$
Friction coefficient (Pull-out)	0.700
Friction coefficient (Direct sliding)	0.700
Soil-reinforcement adhesion (kN/m <sup>2</sup> )	5.000

Reinforcement properties ... Reinforcement Type 2	
Reinforcement material	Sheet or grid
Reinforcement description (16 characters max)	ParaGrid 30/15
Tensile strength (kN/m run)	15.90
Anchorage strength (kN/m run)	15.90
Reinforcement width (m)	1.00
Lateral spacing of Reinforcements (m)	1.00
Soil-reinforcement interaction options	Interaction coefficient
Interaction coefficient	0.900

Reinforcement properties ... Reinforcement Type 3	
Reinforcement material	Strip
Reinforcement description (16 characters max)	Steel strip
Tensile strength (kN/m run)	30.00
Anchorage strength (kN/m run)	30.00
Reinforcement width (m)	0.10
Lateral spacing of Reinforcements (m)	0.90
Soil-reinforcement interaction options	Absolute values of $\mu, c$
Friction coefficient (Pull-out)	0.450
Friction coefficient (Direct sliding)	0.450
Soil-reinforcement adhesion (kN/m <sup>2</sup> )	8.000

Reinforcement properties ... Reinforcement Type 4	
Reinforcement material	Strip
Reinforcement description (16 characters max)	Galvanized steel
Tensile strength (kN/m run)	27.00
Anchorage strength (kN/m run)	27.00
Reinforcement width (m)	0.12
Lateral spacing of Reinforcements (m)	1.25
Soil-reinforcement interaction options	Interaction coefficient
Interaction coefficient	0.850

Reinforcement properties ... Reinforcement Type 5	
Reinforcement material	Nails
Reinforcement description (16 characters max)	Grouted 50mm bar
Tensile strength (kN/m run)	50.00
Anchorage strength (kN/m run)	50.00
Reinforcement width (m)	0.15
Lateral spacing of Reinforcements (m)	1.50
Soil-reinforcement interaction options	Absolute values of $\mu, c$
Friction coefficient (Pull-out)	0.450
Friction coefficient (Direct sliding)	0.450
Soil-reinforcement adhesion (kN/m <sup>2</sup> )	90.00
Alpha factor for nails in cohesive soil	0.500

### Data base of reinforcement types.

SLOPE version 12R includes a data base of reinforcement data. You can select a reinforcement type from the data base and insert its properties into the currently selected reinforcement type. To do this you can press **F1** while editing the Reinforcement description or Tensile strength and select from the list of pre-defined types.

## 14.0 FACTOR of SAFETY SELECTION OPTIONS

Brief results are tabulated for all or some of the slip surfaces analysed. The selection and tabulation options allow you to control the level of detail. To access the options, click on the **Output** tab during data input or click on the blue **Edit FoS selection options** button while viewing results. The options are in two categories:

### 14.1 Exclusions

You can set criteria to exclude some slip surfaces from the tabulated results altogether. They are:

- a) Ignore slip surfaces where the interlock value in any slice is less than a specified value, as discussed in Section 10.1.4. It is recommended to exclude slip surfaces with a value of  $(1 + \tan \alpha \cdot \tan \phi' / F)$  less than 0.1.
- b) Ignore slip surfaces where the slipped mass is less than a specified value. This allows you to exclude slip surfaces from consideration because they are trivial.

Slip surfaces excluded in this way do not feature in the selected results, summary results or graphical output.

### 14.2 Selections

You can limit the number of brief results tabulated for each exit point. The number of results can be restricted in a variety of ways:

- a) List all results (not excluded by the above exclusion rules)
- b) Limit the number of slip surfaces per exit point to the N most critical values (e.g. 10 or 20)
- c) Limit the number of slip surfaces to all those with a FoS below a selected value.

Results not listed because of the selection criteria will still feature in Summary and Graphical results.

### 14.3 Colour options

The graphical display of results shows a grid of factors of safety. The values are colour coded from red via yellow through to green to indicate the criticality of the result. Colour coding options allow you to override the default settings to achieve a more suitable colour scheme. When searching for Maximum factor of safety in a load factor calculation, the colour scale is inverted with red representing the largest factors of safety.

## 15.0 INTERPRETATION OF RESULTS

See Section 3.10 for details of how to view the results on the screen and Section 3.11 for instructions on creating reports.

### 15.1 SELECTED RESULTS

Click the **Selected results** tab to see a selection of brief results for slip surfaces passing through an individual common point (exit point or reinforcement layer). Click the green selection button to see the pop-up menu which allows you to view output for a selected common point (exit point or reinforcement layer).

The number of slip surfaces displayed for each common point (exit point or reinforcement layer) is controlled by the '**FoS selection options**' (see Section 14.0).

The brief results are printed in 7 or 8 columns. In columns 5 to 8 there are two numbers, one bracketed, the other unbracketed, corresponding to the bracketed and unbracketed headings in those columns. All forces and moments are calculated per unit length normal to the section.

The format of the table varies according to the type of slip surface (circle or wedge) and the method of analysis. The following sections describe the layout in some typical cases.

### 15.1.1 Circles analysed by Bishop's or Spencer's method

Brief results for selected circles through common point no.2

---Centre---	Radius	Factor	Slipped	Overturning	Restoring	Delta
X	Y	of	mass	moment	moment	(Itera
		safety	( Out	of balance	forces )	tions)
			( Vert.	Horiz.	Moment )	
			kN/m		kN.m/m	
13.62	46.08	50.82	1.468	12191	112681	165391
			( 0)	( 0)	( 0)	( 4 )
13.62	51.08	55.39	1.475	12450	124793	184098
			( 0)	( 0)	( 0)	( 4 )
13.62	56.08	60.04	1.515	12707	136023	206015
			( 0)	( 0)	( 0)	( 4 )
13.62	41.08	46.34	1.517	11951	99554	151027
			( 0)	( 0)	( 0)	( 4 )
8.62	56.08	58.44	1.565	8440	96211	150559
			( 0)	( 0)	( 0)	( 5 )

Column	Unbracketed	(Bracketed)
1 and 2	<b>Coordinates of centre of circle</b>	-
3	<b>Radius of circle</b>	-
4	<b>Factor of safety</b>	-
5	<b>Slipped mass</b> The total weight of soil above the slip surface.	<b>Out of balance forces</b> Some methods of analysis do not satisfy one, or more of the conditions of overall horizontal, vertical or moment equilibrium of the slipped mass. The out of balance forces give some idea of the possible error in the calculated factor of safety.
6	<b>Overturning moment</b> Total moment about the centre due to self weight of the slipped mass, plus any surcharge loads (including water pressures on submerged slopes).	
7	<b>Restoring moment</b> Total moment about the centre due to the available shearing resistance on the slip surface.	
8	<b>Delta</b> For methods of analysis which assume parallel inclined interslice forces, delta is the calculated inclination (in degrees) of the interslice forces to the horizontal.	<b>Iterations</b> The number of iterations to achieve convergence in the factor of safety calculation.

### 15.1.2 Circles analysed by Janbu (simple) or Reinforced soil method

Brief results for selected circles through common point no.5

---Centre---		Radius R	Factor of safety	Slipped mass ( Reinf.) ( force ) kN/m	Restoring moment (Disturbing) ( moment ) kN.m/m	Out of balance moment ( Iter ) kN.m/m
X	Y					
18.62	31.08	37.20	1.231	12872 ( 69 )	127086 ( 80564 )	-22653 ( 4 )
18.62	36.08	41.46	1.243	13097 ( 69 )	141598 ( 94261 )	-19679 ( 4 )
18.62	41.08	45.88	1.319	13329 ( 69 )	161006 ( 106311 )	-15774 ( 4 )
18.62	26.08	33.13	1.326	12690 ( 69 )	117501 ( 65781 )	-22811 ( 4 )
13.62	41.08	43.88	1.580	8668 ( 69 )	125496 ( 70857 )	-8572 ( 5 )
23.62	21.08	33.03	1.616	20046 ( 69 )	193303 ( 89702 )	-29887 ( 4 )

Column	Unbracketed	(Bracketed)
1 and 2	<b>Coordinates of centre of circle</b>	-
3	<b>Radius of circle</b>	-
4	<b>Factor of safety</b>	-
5	<b>Slipped mass</b> The total weight of soil above the slip surface.	<b>Reinforcement force</b> Total force provided by reinforcement for this slip surface
6	<b>Restoring moment</b> Total moment about the centre due to the available shearing resistance on the slip surface.	<b>Disturbing moment</b> Total moment about the centre due to self weight of the slipped mass, plus any surcharge loads(including water pressures on submerged slopes).
7	<b>Out of balance moment</b> These methods of analysis do not guarantee moment equilibrium. The out of balance moment give some idea of the possible error in the calculated FoS.	<b>Iterations</b> The number of iterations to achieve convergence in the factor of safety calculation.



### 15.1.3 Two- and three-part wedges analysed by Janbu (simple) or Reinforced soil method

Brief results for selected wedges through exit point no.3

Wedge node X	Y	Toe X coord ( Exit angle )	Wedge angle ( Base angle )	Factor of safety	Slipped mass (Reinf.) (force ) kN/m	Restoring force (Disturbing) ( force ) kN/m	Out of balance moment ( Iter ) kN.m/m
46.00	3.18	-4.00 ( 85.00 )	30.00 15.00)	1.187	10941 ( 69 )	3208 ( 2704 )	-15707 ( 4 )
51.00	3.18	-4.00 ( 85.00 )	15.00 15.00)	1.226	12375 ( 69 )	3662 ( 2987 )	-16506 ( 4 )
41.00	3.18	-4.00 ( 85.00 )	45.00 15.00)	1.295	9840 ( 69 )	3009 ( 2324 )	-12485 ( 4 )
46.00	8.18	-4.00 ( 85.00 )	40.00 20.00)	1.335	8519 ( 69 )	2744 ( 2056 )	-9909 ( 4 )
36.00	3.18	-4.00 ( 80.00 )	55.00 15.00)	1.482	9078 ( 69 )	3041 ( 2052 )	-8742 ( 5 )
41.00	8.18	-4.00 ( 80.00 )	60.00 20.00)	1.557	7678 ( 69 )	2646 ( 1699 )	-5663 ( 5 )

Column	Unbracketed	(Bracketed)
1 and 2	<b>Coordinates of wedge node</b>	-
3	<b>Toe x-coordinate</b>	<b>Toe exit angle</b> (for 3 part wedge only)
4	<b>Wedge angle</b>	<b>Base angle</b> (for 3 part wedge only)
5	<b>Factor of safety</b>	-
6	<b>Slipped mass</b> The total weight of soil above the slip surface.	<b>Reinforcement force</b> Total force provided by reinforcement for this slip surface
7	<b>Overturning moment</b> Total moment about the centre due to self weight of the slipped mass, plus any surcharge loads (including water pressures on submerged slopes).	<b>Restoring moment</b> Total moment about the centre due to the available shearing resistance on the slip surface.
8	<b>Out of balance moment</b> These methods of analysis do not guarantee moment. The out of balance moment gives some idea of the possible error in the calculated FoS.	<b>Iterations</b> The number of iterations to achieve convergence in the factor of safety calculation.

## 15.2 MESSAGES DURING ANALYSIS

Note: For errors during input and editing see Section 3.4.

### **Minimum number of slices reduced to N**

The minimum number of slices specified by the user has led to the section being subdivided into more than 100 slices (the maximum permitted). The program has taken appropriate corrective measures. No further action is required by the user. The reduced number of slices will remain in force for the rest of the analysis.

### **Moment convention reversed**

The program has found that the assumed direction of slip has given rise to a negative overturning moment. It has continued the calculation on the assumption that the slip occurs in the opposite direction. If this second assumption also leads to negative overturning moments the following error message is printed:-

### **Ill-conditioned problem; Negative overturning moments**

This situation can occur due to injudicious choice of the magnitude of surcharge loads when calculating factors of safety on surcharge loads (see Section 10.2.2).

### **Not analysed - no loads on slipped mass**

Cannot calculate a factor of safety on surcharge loads for this slip surface because there are none on this mass of soil.

### **Circle not analysed - too large or too small.**

The circle either did not intersect the ground at all or intersected ground level beyond the limits of the section.

### **Circles not analysed - all too large or too small.**

As above but this applies to a group of circles from the same centre. Only applies where the radii are defined by an initial radius and increment of radius.

### **Data error - all circles were too large or too small.**

The specified centres and radii did not form any valid slip surfaces (see Section 9.1).

### **Circle not analysed - centre lies below exit point.**

Such circles are not kinematically plausible and are therefore not analysed.

**No valid wedges**

For the given wedge node, none of the wedge angles and exit points produced a valid 2 or 3 part wedge. This message appears only when Standard Output has been selected and the program does therefore not give separate output for each trial wedge associated with this wedge node.

**Wedge node above ground level****Wedge node outside section****Wedge node at same X coord as exit point****No wedge intersection****Concave wedge intersection****Toe wedge above GL****X coords out of sequence****Internal angle too small**

The above messages all indicate that a particular set of wedge angles and exit point did not yield a valid wedge. These messages appear only when Extra Output has been selected and the program gives separate output for each trial wedge.

**Factor of safety was greater than 1000.**

Larger values are not reported.

**Negative effective stress on base of Slice No. nnn**

The calculated effective stress normal to the base of the given slice is less than zero and this would give rise to the calculation of a corresponding negative value of shear resistance in accordance with Equation 6.1. Such negative values of shear resistance are automatically reset to zero by the program since Equation 6.1 only applies when the result is positive.

This problem usually arises due to excessively high pore pressures on the base of the slice. However it can also occur locally when using analysis methods Nos. 4 or 5 (inclined interslice forces, see Section 10.1) if there are excessively rapid lateral changes of pore pressure across individual slices. The data should be examined to see if the problem has been defined in a reasonable way.

**Load factor not found or  
Convergence failure in Load Factor calculation**

Cannot calculate a factor of safety on surcharge loads for this slip surface. Try different values for the given surcharges i.e. scale them all up or down.

**Convergence failure in factor of safety calc.**

The required degree of convergence has not been reached after 60 iterations. The factors of safety in the last 10 iterations are listed.

The methods of analysis with parallel inclined interslice forces are vulnerable to this problem as it is not always possible to find a force inclination which satisfies all the conditions of equilibrium. Use a simpler method of analysis.

**Interlock problem**

The force distribution in one or more slices suffers from the interlock condition described in Section 10.1.4. The affected slices are listed as follows:-

$$(1 + \tan \alpha \cdot \tan \phi' / F) = \text{xxxx in slice } n$$

where  $\alpha$  is the inclination to the horizontal of the base of the slice,  $\phi'$  is the angle of friction on the base of the slice and  $F$  is the factor of safety. The message is printed for all slices in which  $\text{xxxx}$  is less than 0.5. The calculated factor of safety may be grossly in error when  $\text{xxxx}$  is less than 0.10. Check the force distribution in the affected slices to see if it is having a disproportionate effect on the factor of safety.

**Nett overturning moment is small compared with total soil weight or surcharge loads**

The nett overturning moment is the difference of two large quantities and may therefore be in error. The true factor of safety is probably quite large anyway but the calculated value should be treated with caution

## 15.3 SUMMARY RESULTS FOR CIRCLES AND NON-CIRCLES

Summary results begin with a resumé of the Method of analysis, Partial factors and Exclusion options

### Analysis options

Method of analysis: BISHOP - Simplified : Horizontal interslice forces  
Factors of safety calculated on Soil Strength

Partial factor of safety on tan(phi) = 1.000  
Partial factor of safety on drained cohesion = 1.000  
Partial factor of safety on undrained cohesion = 1.000

### Exclusion options

The summary results and selected results for each exit point exclude:  
All slip surfaces where the interlock value in any slice is less than 0.10  
All slip surfaces where the slipped mass is less than 1.0 kN/m run

There follows a table summarising the critical factors of safety for each common point (circular arc analysis) or exit point (wedge analysis). For a reinforced soil design the summary table shows the critical wedge at each reinforcement elevation and the total required force to maintain equilibrium at that elevation.

The summary output concludes with a diagrammatic presentation of the factors of safety. A rectangular array corresponding to the grid of centres or wedge nodes shows the factor of safety at each grid position.

### 15.3.1 Critical factor of safety for each common point (circular arc analysis)

Critical Factor of Safety for each Common Point

---- Common point ----			----- Critical circle -----			Total Reinf. force	
Point no.	X coord	Y coord	---- Centre X	---- Y	Radius		Factor of safety
1	-2.00	0.00	-2.00	9.00	9.01	1.017	108
2	-1.50	0.00	-1.00	7.00	7.02	0.950	101
3	-1.00	0.00	-1.00	7.00	7.02	0.950	101
4	-0.50	0.00	-1.00	7.00	7.02	0.950	101
5	0.00	0.00	-1.00	7.00	7.07	1.055	130

This table gives the critical factor of safety and coordinates of the critical circle for each common point. If reinforcement is present, the total reinforcement force for the critical circle is also shown.

### 15.3.2 Critical factor of safety for each exit Point (Two and three part wedges)

Critical Factor of Safety for each Exit Point								
- Exit point -		----- Critical wedge -----						
Point	X	-- Wedge node --		Wedge	Base	Exit	Factor of	Total
no.	coord	X	Y	angle	angle	angle	safety	Reinf. force
1	1.82	2.55	5.45	15.00	-	-	1.128	0
2	1.15	2.55	5.45	20.00	-	-	2.392	65
3	0.60	2.31	5.45	25.00	-	-	3.318	133
4	0.00	2.31	5.45	20.00	-	-	3.842	230

This table gives the critical factor of safety and coordinates of the critical wedge for each exit point. Base and exit angles are only relevant for three part wedges. If reinforcement is present, the total reinforcement force for the critical wedge is also shown.

### 15.3.3 Diagrammatic print-out of factors of safety at Circle centres and Wedge nodes

For circular arc and wedge analyses, the output concludes with a diagrammatic presentation of the factors of safety. A rectangular array corresponding to the grid of centres or wedge nodes shows the factor of safety at each grid position. In the case of automatic wedge generation (reinforced soil analysis) the grid of nodes is not necessarily equally spaced since the wedge nodes follow the reinforcement layers.

Where more than one circle or wedge was analysed from a given centre or node, the program prints the critical factor of safety from amongst all the circles or wedges from that centre or node.

Where the grid is too wide to fit on one sheet it is split into sections. Each section is announced with the words 'continuation sheet'.

A dot is printed at grid positions where no analysis was carried out. An asterisk is printed where the factor of safety was greater than 10. If all the factors of safety were greater than 10 they are scaled down for ease of printing and a warning note is added 'All factors of safety have been divided by 10'.

The following grid of factors of safety was created by automatic wedge generation for a reinforced soil slope:

FACTORS OF SAFETY AT WEDGE NODES																			
		X-coordinates																	
Y-coord		0.0	0.2	0.4	0.6	0.9	1.2	1.3	1.4	1.5	1.6	1.8	2.0	2.1	2.2	2.3	2.4	2.5	2.6
5.45	.	.	.	.	.	.	.	.	.	.	.	2.774	2.232	1.903	.	1.614	1.359	.	1.128
4.45	.	.	.	.	.	.	.	.	2.236	.	1.929	.	.	1.710	.	.	1.505	.	.
3.45	.	.	.	.	.	1.542	.	.	.	.	1.265	.	.	.	.	1.247	.	.	.
2.55	.	.	.	.	1.398	.	.	.	.	1.178	.	.	.	.	1.255	.	.	.	.
1.80	.	.	.	1.400	.	.	.	.	1.179	.	.	.	.	.	.	1.149	.	.	.
1.15	.	.	1.319	.	.	.	.	1.102	.	.	.	.	.	.	.	1.129	.	.	.
0.55	.	1.274	.	.	.	.	1.078	.	.	.	.	.	.	.	.	1.072	.	.	.
0.00	1.254	.	.	.	.	1.066	.	.	.	.	.	.	.	.	.	1.068	.	.	.

Note: Irregular grid spacing; Wedge nodes positioned along reinforcement

Continuation sheet																			
		X-coordinates																	
Y-coord		2.9	3.0	3.2	3.4	3.5	3.6	3.7	4.1	4.2	4.4	4.5	4.6	4.9	5.0	5.4	5.8	6.1	
5.45	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
4.45	1.308	.	1.113	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.
3.45	.	1.328	.	.	.	1.284	.	.	1.171	.	.	.	.	.	.	.	.	.	.
2.55	.	1.223	.	.	.	.	1.203	.	.	.	1.107	.	.	.	.	.	.	.	.
1.80	.	.	1.192	.	.	.	.	1.135	.	.	.	.	.	1.101	.	.	.	.	.
1.15	.	.	.	1.128	.	.	.	.	1.147	.	.	.	.	.	1.104	.	.	.	.
0.55	.	.	.	.	1.153	.	.	.	.	.	1.156	.	.	.	.	1.105	.	.	.
0.00	.	.	.	.	.	.	1.121	.	.	.	.	.	1.157	.	.	.	1.103	.	.

Note: Irregular grid spacing; Wedge nodes positioned along reinforcement

## 15.4 CRITICAL SLIP SURFACE

The Summary Results section concludes with details of the overall critical slip surface.

For circular arc and wedge analyses the program chooses the circle or wedge with the least factor of safety of all those analysed. For a general non-circular slip, detailed results are displayed for the defined surface.

### Analysis options

Method of analysis: BISHOP - Simplified : Horizontal interslice forces  
Factors of safety calculated on Soil Strength

Partial factor of safety on tan(phi) = 1.000  
Partial factor of safety on drained cohesion = 1.000  
Partial factor of safety on undrained cohesion = 1.000

### DETAILED RESULTS FOR CRITICAL CIRCLE

**Factor of safety = 1.443**

Slipped mass = 11393 kN/m      Out of balance vertical force = 0 kN/m  
Out of balance horizontal force = 273 kN/m

Centre of circle: X = 13.62    Y = 51.08    Radius = 54.65

Overturning moment = 115509 kN.m/m    Restoring moment = 166659 kN.m/m

Details of the forces on each slice are printed in four tables:

- Table 1: Forces on slice interfaces.
- Table 2: Weight and forces on the base of each slice
- Table 3: Surcharge loads and water pressures on submerged ground.
- Table 4: Reinforcement forces

Slices and their interfaces are numbered in order of increasing x coordinate (regardless of the direction of failure). Table 3 is omitted if all surcharge loads are zero and there are no submerged slopes. Table 4 is omitted if there is no reinforcement. The tables are described in detail below.

### Detailed results - Table 1 : Slice interfaces

Slip surface coordinates ----- No.	Piezometric		elevation Y(w)	Interslice forces		vertical Q kN/m
	X	Y		horizontal	E'(effective)	
				E(total) kN/m	E'(effective) kN/m	
1	9.30	3.72	16.00	0	0	0
2	19.34	0.46	16.00	1239	390	0
3	29.89	0.34	16.00	1965	843	0
4	40.00	3.38	16.00	1734	952	0
5	43.00	4.98	22.98	1453	1380	0
6	50.00	10.51	24.38	366	-241	0
7	52.00	12.73	23.27	27	-314	0
8	53.00	14.00	22.63	-125	-347	0
9	55.00	16.97	8.00	-312	-312	0
10	55.01	16.99	8.00	-313	-313	0
11	56.40	19.54	7.79	-343	-343	0

Heading	Units (example only)	Interpretation
X	m	X coordinate of boundary between slices
Y	m	Y coordinate of slip surface
Y(w)	m	Y coordinate of piezometric elevation at the slip surface
E	kN/m run	Total horizontal force between slices
E'	kN/m run	Effective horizontal force between slices
Q	kN/m run	Shear force between slices



**Detailed results - Table 2 : Base forces and slice weight**

Slice No.	Cohesion	Tan(phi)	Pore pressure	Weight of slice	Forces on base of slice		
	(avge) kN/m <sup>2</sup>	(avge)	(avge) kN/m <sup>2</sup>	W kN/m	--- normal P kN/m	--- P' kN/m	of slice shear S kN/m
1	6.78	0.6874	136.45	761	1944	504	247
2	10.00	0.5774	153.01	2081	2723	1108	440
3	10.00	0.5774	138.71	2562	2735	1271	496
4	8.90	0.5561	150.20	774	815	304	118
5	0.00	0.3839	156.33	1563	1900	507	115
6	0.00	0.3839	119.73	342	481	123	28
7	0.00	0.3839	94.04	134	203	51	11
8	0.00	0.3971	20.77	177	254	179	42
9	0.00	0.5774	0.00	1	1	1	0
10	0.00	0.7177	0.00	38	44	44	19

<b>Heading</b>	<b>Units (example only)</b>	<b>Interpretation</b>
Cohesion (avge)	kN/m <sup>2</sup>	Average cohesion on base of slice
Tan(phi) (avge)	-	Average tangent of angle of shearing resistance on base of slice
Pore pressure (avge)	kN/m <sup>2</sup>	Average pore pressure on base of slice
W	kN/m run	Total weight of slice
P	kN/m run	Total normal force on base of slice
P'	kN/m run	Effective normal force on base of slice
S	kN/m run	Mobilised shear resistance on base of slice

**Detailed results - Table 3 : Surcharge loads**

Slice No.	-- Surcharge loads --		Water load on submerged ground	
	vertical load	horizontal load	vertical	horizontal
	kN/m run	kN/m run	kN/m run	kN/m run
1	0	0	1012	405
2	0	0	637	255
3	0	0	200	80
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0

<b>Heading</b>	<b>Units (example only)</b>	<b>Interpretation</b>
Surcharge load	kN/m run	Vertical and horizontal surcharge loads (force per unit length perpendicular to the plane of the analysis; see Section 8.0)
Water load	kN/m run	Vertical and horizontal components of water load on submerged ground (force per unit length perpendicular to the plane of the analysis)

**Detailed results - Table 4 : Reinforcement forces**

Layer No.	Elev.	Inside slip surface		Outside slip surface		Available Reinforcement force kN/m run	
		Length m	Pull-out kN/m run	Length m	Pull-out kN/m run		
1	5.65	No intersection					
2	4.65	0.92	39.00w	0.58	15.51	15.51	
3	3.65	1.07	39.00a	1.91	39.00w	39.00	
4	2.65	1.23	39.00	2.24	39.00w	39.00	
5	1.85	1.23	39.00w	3.05	39.00a	39.00	

Note: 'a' indicates end of reinforcement is anchored  
'w' indicates end of reinforcement is wrapped around

<b>Heading</b>	<b>Interpretation</b>
Elev.	Elevation of reinforcement layer
Inside slip surface ----- Length    Pull-out	Length and Pull-out resistance of the segment of this reinforcement layer lying within the slipped mass
Outside slip surface ----- Length    Pull-out	Length and Pull-out resistance of the segment of this reinforcement layer lying outside the slipped mass
Available Reinforcement force	The nett available reinforcement resistance provided by this layer; the lesser of the two previous values

## 15.5 REINFORCED SOIL DESIGN SUMMARY

The summary table shows the critical wedge at each reinforcement elevation and the total required force to maintain equilibrium of the critical wedge exiting at that elevation.

REINFORCED SLOPE DESIGN										
Layers of reinforcement and Critical wedges for exit point at each elevation.										
----- Reinforcement layer -----						----- Critical wedge -----				
No.	Elev.	Type	X coordinates		Design load	Mob. load	Wedge node X	Wedge node Y	Wedge angle	Required force
			X1	X2	kN/m	kN/m			(deg)	kN/m
1	5.45	1	1.82	2.55	32.5	2.1	1.97	5.45	35.0	2.1
2	4.45	1	1.48	3.20	32.5	13.1	1.83	4.45	35.0	13.1
3	3.45	1	1.15	4.15	32.5	32.5	1.85	3.45	30.0	33.1
4	2.55	1	0.85	4.45	32.5	32.5	1.75	2.55	30.0	59.2
5	1.80	1	0.60	5.00	32.5	32.5	1.60	1.80	35.0	87.0
6	1.15	1	0.38	5.35	32.5	32.5	1.53	1.15	35.0	115.1
7	0.55	1	0.18	5.75	32.5	32.5	1.48	0.55	35.0	144.5
8	0.00	1	0.00	6.10	32.5	32.5	1.40	0.00	35.0	174.5
		Reinforcement type	1	Total reinforcement area		= 30.08 m2 per m run				

Heading	Interpretation
Elev.	Elevation of this layer of reinforcement
Type	Type of reinforcement as listed in the reinforcement properties
X coordinates	X coordinates of the ends of the reinforcement layer
Design load	Available load capacity of this layer
Mob. load	Mobilised load in this layer
Critical wedge	The wedge which exits at this elevation which requires the maximum force to maintain stability
Required force	The force which must be provided by reinforcement (at or above this elevation) to maintain stability

The critical wedge at each reinforcement elevation is the wedge which requires the greatest restoring force (from the reinforcement) to maintain equilibrium.

### 15.5.1 Spacing of reinforcement layers

If the base layers are very close together you should consider defining some additional stronger types of reinforcement to achieve more uniform spacing. If all layers are at their maximum spacing you should consider defining some additional weaker types of reinforcement to achieve a more economical design.

The more comprehensive the range of reinforcement strengths defined in the reinforcement properties section, the more economical will be the resulting design.

### **15.5.2 Back-analysis of the design to check overall FoS**

The file (mydataX.DAT) containing the designed reinforcement can be back-analysed and checked immediately for overall factor of safety; simply select **Analyse** at Menu 2. The program carries out a 2 part wedge analysis using the automatic wedge generation option. You may well find that the minimum factor of safety calculated during this back-analysis falls marginally (typically 3% to 5%) below the Overall FoS specified for the design.

This failure to achieve the specified design criterion can be overcome at the design stage by specifying a marginally higher design FoS than is actually required. A 5% margin is recommended. Thus if you want to achieve an overall FoS of 1.10 then your design data should specify an Overall Design FoS of about 1.15 .

### **15.5.3 Messages during reinforcement design**

**No reinforcement required** The slope has the required factor of safety without any reinforcement.

#### **Vertical spacing of reinforcement layers is less than the specified minimum. Use stronger reinforcement**

The given reinforcement strength(s) lead to an excessive number of reinforcement layers at close spacings.

#### **Base layer of reinforcement is too long or did not intersect GL**

The specified base layer is inappropriately placed.

#### **No point in extending this layer:**

This usually arises in cases where the reinforcement is specified as anchored rather than wrapped around. It may be necessary to make some manual adjustment to the upper few layers of reinforcement.

**The layer of reinforcement at elevation yyyy has been extended as far as the other side of the slope and has still not mobilised a pull-out resistance equal to the tensile strength of the reinforcement. Do you want this layer (and others in the same condition) to be anchored at their far end?**

The usual answer to this question is "yes". If you answer "no" the design is likely to be incomplete (i.e. unstable).

This situation is most likely to arise in a narrow embankment where stability can only be achieved by layers of reinforcement running the full width of the embankment, anchored or wrapped around at both faces.

### **Reinforcement lengths rationalised**

You have specified Parallel or Vertical truncation in the design options. The lengths of reinforcement required for stability have now been adjusted to make a more practical installation arrangement.

### **The current data set now includes the designed reinforcement. A copy of the data set is stored in *filename***

The original data file (e.g. mydata.DAT) remains as it was at the start of the design and a new data file (mydata\_RSD.DAT) has been created and contains the reinforcement design.

### **Cannot design more than 100 layers of reinforcement**

Larger versions of the program can be created by special arrangement.

## **15.6 GRAPHICAL OUTPUT**

An example of the SLOPE Desktop in View Results mode is shown in Figure 12b. A detail of the graphical output is shown on page A8 in Appendix A.

### **The slope profile**

This is the same as during data input except that you cannot click and drag to edit any of the data values in **View results** mode.

### **The grid of centres or wedge nodes**

This is the grid defined in the data plus any additional grid points analysed using the **Extended grid** option.

**Factors of safety at grid points**

These are shown to a maximum of 3 decimal places. If space is lacking then 2 or only 1 decimal place is shown. Click and drag to select part of the section for detailed viewing as described in Section 3.1.3.

**Common points / Exit points**

Common points are marked with red crosses and are numbered

**Critical slip surface(s)**

For **Selected output** the critical slip surface for a particular common/exit point is shown.

For **Summary output** the critical slip surface for each of the common/exit points is shown (in red).

**Colour coded grid squares**

The colour codes correspond to the value of factor of safety at each grid point. The squares are colour coded on a scale from red (most critical) through yellow to green (least critical). The default colour mapping is usually adequate but you can customise it by clicking on the pale blue **Edit FoS selection options** button.

**Required force for reinforced soil design**

The required force for the critical wedge at each reinforcement layer is shown in red

## APPENDIX A Example data and results

Limited Operation Demonstration Version	Sheet No.
Program: SLOPE Version 12R.01 Revision A09.B06.R31	
Licensed from GEOSOLVE	Job No.
Run ID: Demo9a	Made by :
Gravity retaining wall	Date:10-08-2005
Overall stability	Checked :

Units: kN,m

**INPUT DATA****PROFILE DATA**

Grid line	1	2	3	4	5	6	7	8
X-Coord	-155.76	-4.92	1.00	20.04	29.90	30.00	40.00	40.24

Stratum	Y-Coordinates							
1 (GL)	-10.08	-8.40	-5.27	2.60	2.60	2.60	2.60	2.60
2	-10.08	-8.40	-5.27	2.60	2.60	2.60	2.60	2.60
3	-10.08	-8.40	-5.28	-5.02	-5.00	-0.30	-0.30	2.60
4	-10.08	-8.40	-5.28	-5.02	-5.00	-5.00	-5.00	-5.00
5	-79.80	-69.00	-68.27	-65.91	-64.69	-64.67	-63.44	-63.41

Grid line	9	10	11	12	13	14	15	16
X-Coord	42.52	48.14	49.86	52.20	56.12	72.90	73.00	250.00

Stratum	Y-Coordinates							
1 (GL)	30.90	30.90	31.42	32.12	33.30	38.35	38.38	40.90
2	30.90	30.90	23.81	14.17	14.27	14.70	14.71	19.30
3	30.90	30.90	23.81	14.17	-0.30	-0.30	-5.00	-0.70
4	-5.00	-5.00	-5.00	-5.00	-5.00	-5.00	-5.00	-0.70
5	-63.12	-62.43	-62.21	-61.92	-61.44	-59.36	-59.35	-37.42

**SOIL PROPERTIES**

----- S t r a t u m ----- No.	Description	Bulk unit wt.		-----Strength parameters-----			Datum for C
		below GWL kN/m3	above GWL kN/m3	C kN/m2	Phi (deg)	dC/dY kN/m2/m	
1	Silty sand	20.00	19.00	0.00	28.00	Piezometric surface	
2	Thames gravel	25.00	25.00	0.00	50.00		
3	Gravity wall	25.00	25.00	1000.0	0.00		
4	London Clay	20.00	20.00	10.00	23.00		
5	Chalk	22.00	22.00	300.00	20.00		

**GROUND WATER CONDITIONS**

Unit wt. of water = 10.00 kN/m3

Grid line	1	2	3	4	5	6	7	8
X-Coord	-155.76	-4.92	1.00	20.04	29.90	30.00	40.00	40.24

Ground water level	-13.44	-10.65	-10.54	-10.18	-10.00	-9.97	-7.38	-7.29
--------------------	--------	--------	--------	--------	--------	-------	-------	-------

Grid line	9	10	11	12	13	14	15	16
X-Coord	42.52	48.14	49.86	52.20	56.12	72.90	73.00	250.00

Ground water level	-6.34	-4.02	-3.37	-2.48	-1.00	3.00	3.00	10.00
--------------------	-------	-------	-------	-------	-------	------	------	-------

**Piezometric surfaces associated with individual strata**

Grid line	1	2	3	4	5	6	7	8
X-Coord	-155.76	-4.92	1.00	20.04	29.90	30.00	40.00	40.24

Surface	Piezometric elevation							
1	23.82	23.82	23.82	23.82	23.82	23.82	23.82	23.82

Grid line	9	10	11	12	13	14	15	16
X-Coord	42.52	48.14	49.86	52.20	56.12	72.90	73.00	250.00

Surface	Piezometric elevation							
1	23.82	23.82	23.82	24.26	25.00	28.15	28.15	35.64



**SURCHARGE LOADS**

Load No.	Loaded area		---- Line load -----		Equiv. distrib. load	
	from	to	vertical kN/m run	horizontal kN/m run	vertical kN/m2	horizontal kN/m2
1	48.14	73.00 D	( 497.2)	( 0)	20.00	0

**CIRCULAR SLIP SURFACE DATA**

Grid of centres:	X	Y
Corner of grid	-42.00	40.00
Grid increment	12.00	12.00
No. of grid lines	13	12

The grid of centres will be extended automatically until a minimum factor of safety has been found.

Common point(s):	X	Y
Coordinates of (first) point	73.00	-5.11
Increment between points	0.00	-8.00

Number of points = 5

**ANALYSIS OPTIONS**

Method of analysis: BISHOP - Simplified : Horizontal interslice forces  
 Factors of safety calculated on Soil Strength  
 Partial factor of safety on tan(phi) = 1.000  
 Partial factor of safety on drained cohesion = 1.000  
 Partial factor of safety on undrained cohesion = 1.000  
 Partial factor of safety on soil weight = 1.000  
 Partial factor of safety on surcharge loads = 1.000  
 Minimum number of slices = 12

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 69 Rodenhurst Road, London SW4, UK. www.geosolve.co.uk

Run ID. Demo9a	Made by :
Gravity retaining wall	Date:10-08-2005
Overall stability	Checked :

-----  
 Brief results for selected circles through common point no.1

---Centre---		Radius R	Factor of safety	Slipped mass ( Out of ( Vert. kN/m	Overturning moment of balance Horiz.	Restoring moment forces ) Moment )	Delta (Itera tions)
X	Y						
18.00	40.00	71.13	1.274	80684	1841167	2345849	( 5 )
18.00	52.00	79.29	1.290	77655	2072883	2673426	( 5 )
6.00	64.00	96.25	1.324	93136	2786960	3690935	( 5 )
18.00	64.00	88.32	1.332	76174	2307331	3073955	( 6 )
6.00	52.00	88.04	1.337	97868	2553015	3412296	( 5 )
6.00	76.00	105.20	1.345	89861	3021387	4065079	( 5 )
6.00	88.00	114.71	1.390	87777	3256559	4528177	( 5 )
6.00	40.00	80.77	1.394	104472	2320363	3235554	( 5 )
18.00	76.00	98.00	1.401	75595	2542824	3562445	( 6 )
30.00	40.00	62.32	1.404	65041	1366203	1917618	( 6 )

Run ID. Demo9a  
 Gravity retaining wall  
 Overall stability

| Made by :  
 | Date:10-08-2005  
 | Checked :

-----  
 Brief results for selected circles through common point no.2

---Centre---		Radius R	Factor of safety	Slipped mass ( Out ( Vert. kN/m	Overturning moment of balance Horiz.	Restoring moment forces ) Moment ) kN.m/m	Delta (Itera tions)
X	Y						
18.00	52.00	85.23	1.343	99225 ( 0)	2572757 ( 0)	3456301 ( 0)	( 5 )
18.00	40.00	76.46	1.358	99843 ( 0)	2240229 ( 0)	3041530 ( 0)	( 5 )
18.00	64.00	94.71	1.361	99550 ( 0)	2907086 ( 0)	3957610 ( 0)	( 5 )
6.00	64.00	102.15	1.382	117406 ( 0)	3376520 ( 0)	4665799 ( 0)	( 5 )
6.00	76.00	111.49	1.387	115970 ( 0)	3709700 ( 0)	5144768 ( 0)	( 5 )
18.00	76.00	104.72	1.398	100430 ( 0)	3243260 ( 0)	4534576 ( 0)	( 5 )
30.00	40.00	68.33	1.400	83361 ( 0)	1765759 ( 0)	2472104 ( 0)	( 5 )
6.00	52.00	93.42	1.403	119934 ( 0)	3044553 ( 0)	4272646 ( 0)	( 5 )
6.00	88.00	121.29	1.411	115260 ( 0)	4039703 ( 0)	5699309 ( 0)	( 5 )
30.00	52.00	78.03	1.418	85667 ( 0)	2099445 ( 0)	2977741 ( 0)	( 5 )

Gravity retaining wall  
 Overall stability

| Date:10-08-2005  
 | Checked :

-----  
 Brief results for selected circles through common point no.3

---Centre---		Radius R	Factor of safety	Slipped mass ( Out ( Vert. kN/m	Overturning moment of balance Horiz.	Restoring moment forces ) Moment ) kN.m/m	Delta (Itera tions)
X	Y						
6.00	76.00	117.98	1.385	145672 ( 0)	4473141 ( 0)	6194559 ( 0)	( 5 )
18.00	52.00	91.49	1.389	124106 ( 0)	3139430 ( 0)	4360218 ( 0)	( 5 )
18.00	64.00	101.33	1.395	126348 ( 0)	3572438 ( 0)	4982936 ( 0)	( 5 )
18.00	40.00	82.21	1.413	122590 ( 0)	2706045 ( 0)	3823665 ( 0)	( 5 )
18.00	76.00	111.60	1.418	128981 ( 0)	4007300 ( 0)	5681543 ( 0)	( 5 )
30.00	52.00	84.82	1.428	109772 ( 0)	2660708 ( 0)	3799825 ( 0)	( 5 )
30.00	40.00	74.72	1.432	105673 ( 0)	2233088 ( 0)	3197097 ( 0)	( 5 )
6.00	64.00	108.32	1.440	145580 ( 0)	4052687 ( 0)	5837537 ( 0)	( 5 )
30.00	64.00	95.35	1.451	114070 ( 0)	3095513 ( 0)	4492366 ( 0)	( 5 )
6.00	88.00	128.04	1.452	146643 ( 0)	4907504 ( 0)	7123252 ( 0)	( 5 )

Run ID. Demo9a  
Gravity retaining wall  
Overall stability

| Made by :  
| Date:10-08-2005  
| Checked :

-----  
Brief results for selected circles through common point no.4

---Centre---	Radius	Factor	Slipped	Overturning	Restoring	Delta	
X          Y	R	of	mass	moment	moment	(Itera	
		safety	( Out	of balance	forces )	tions)	
			( Vert.	Horiz.	Moment )		
			kN/m		kN.m/m		
18.00	64.00	108.14	1.447	156875	4299606	6222115	( 5 )
				( 0)	( 0)	( 0)	
18.00	52.00	98.00	1.454	152732	3770099	5480155	( 5 )
				( 0)	( 0)	( 0)	
18.00	76.00	118.63	1.455	161297	4836222	7036202	( 5 )
				( 0)	( 0)	( 0)	
30.00	52.00	91.80	1.456	137493	3292969	4796129	( 5 )
				( 0)	( 0)	( 0)	
30.00	64.00	102.56	1.463	143925	3826407	5599577	( 5 )
				( 0)	( 0)	( 0)	
18.00	88.00	129.38	1.473	165824	5374869	7915749	( 5 )
				( 0)	( 0)	( 0)	
30.00	40.00	81.39	1.475	131539	2769098	4083880	( 5 )
				( 0)	( 0)	( 0)	
30.00	76.00	113.56	1.483	149946	4358702	6461898	( 5 )
				( 0)	( 0)	( 0)	
18.00	40.00	88.32	1.486	148829	3238311	4812830	( 5 )
				( 0)	( 0)	( 0)	
6.00	76.00	124.65	1.497	179483	5321541	7964104	( 5 )
				( 0)	( 0)	( 0)	

Run ID. Demo9a  
Gravity retaining wall  
Overall stability

| Made by :  
| Date:10-08-2005  
| Checked :

-----  
Brief results for selected circles through common point no.5

---Centre---	Radius	Factor	Slipped	Overturning	Restoring	Delta	
X          Y	R	of	mass	moment	moment	(Itera	
		safety	( Out	of balance	forces )	tions)	
			( Vert.	Horiz.	Moment )		
			kN/m		kN.m/m		
18.00	52.00	104.72	1.509	185385	4467181	6741563	( 4 )
				( 0)	( 0)	( 0)	
18.00	64.00	115.10	1.537	191609	5100626	7839115	( 5 )
				( 0)	( 0)	( 0)	
30.00	52.00	98.94	1.539	169820	4000328	6158429	( 5 )
				( 0)	( 0)	( 0)	
6.00	76.00	131.46	1.544	216753	6230891	9620762	( 4 )
				( 0)	( 0)	( 0)	
18.00	76.00	125.77	1.547	197881	5739581	8876555	( 5 )
				( 0)	( 0)	( 0)	
30.00	64.00	109.87	1.555	177511	4620726	7184668	( 5 )
				( 0)	( 0)	( 0)	
30.00	40.00	88.29	1.557	161325	3366229	5240843	( 5 )
				( 0)	( 0)	( 0)	
6.00	64.00	121.29	1.558	212494	5594575	8714685	( 4 )
				( 0)	( 0)	( 0)	
18.00	88.00	136.66	1.566	204128	6381396	9992735	( 5 )
				( 0)	( 0)	( 0)	
30.00	76.00	121.01	1.576	185393	5260775	8289102	( 5 )
				( 0)	( 0)	( 0)	





## DETAILED RESULTS FOR CRITICAL CIRCLE - continued

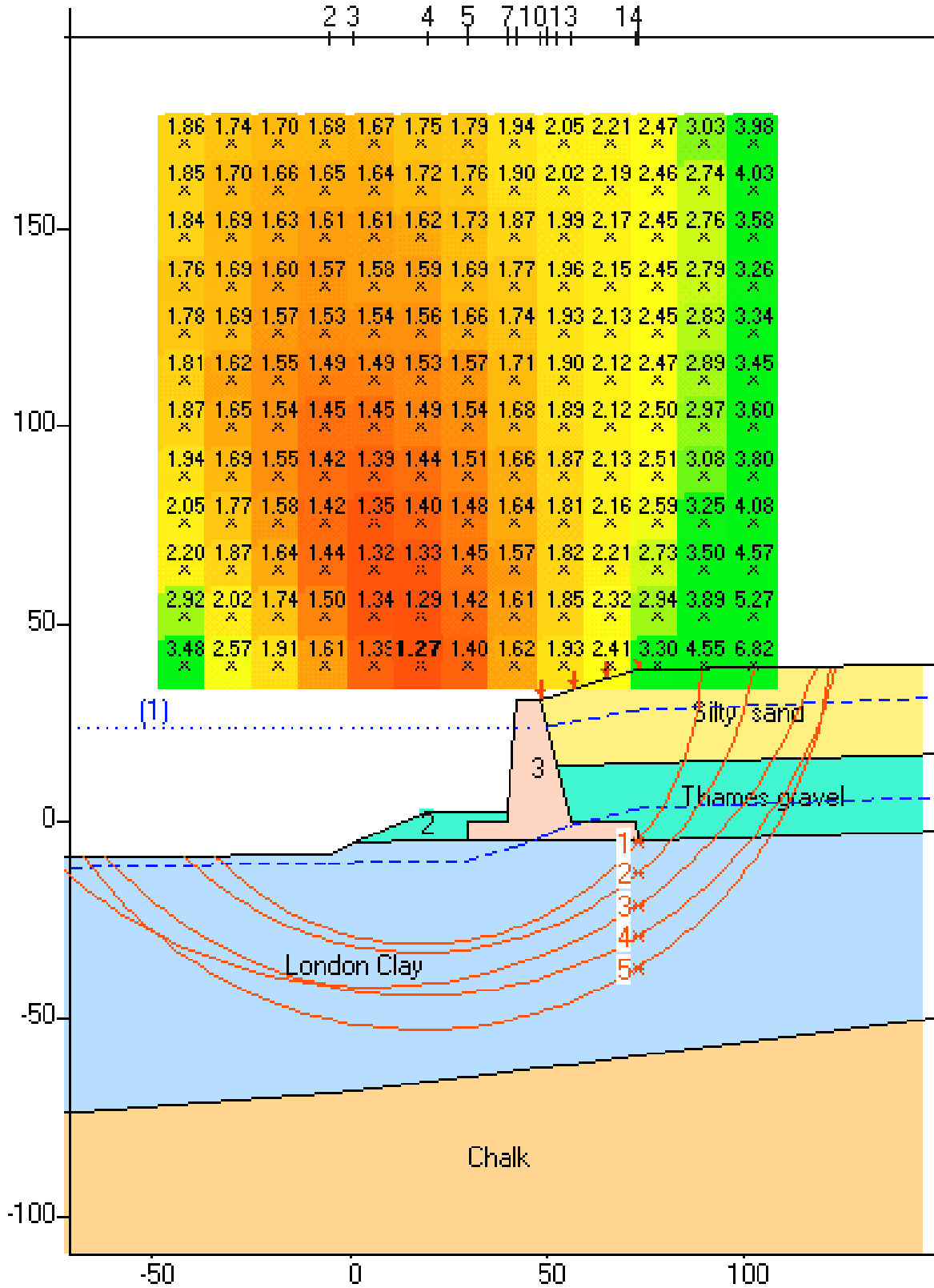
Slice No.	Cohesion (avge) kN/m <sup>2</sup>	Tan(phi) (avge)	Pore pressure (avge) kN/m <sup>2</sup>	Weight of slice W kN/m	Forces on base of slice		
					--- normal P kN/m	--- P' kN/m	shear S kN/m
1	10.00	0.4244	18.79	673	1322	1105	459
2	10.00	0.4244	86.73	2145	3049	2046	772
3	10.00	0.4244	142.93	3517	4248	2596	955
4	10.00	0.4244	176.14	2530	2819	1733	626
5	10.00	0.4244	194.53	5114	5413	3546	1257
6	10.00	0.4244	206.45	6321	6385	4404	1542
7	10.00	0.4244	205.25	6925	6795	4761	1664
8	10.00	0.4244	201.34	69	67	47	16
9	10.00	0.4244	201.99	6676	6493	4412	1551
10	10.00	0.4244	202.70	154	151	99	35
11	10.00	0.4244	203.55	2251	2181	1689	582
12	10.00	0.4244	204.20	7360	7135	5892	2010
13	10.00	0.4244	203.20	2170	2156	1768	604
14	10.00	0.4244	200.58	2813	2819	2289	783
15	10.00	0.4244	194.71	4532	4602	3716	1273
16	10.00	0.4244	167.51	9905	10413	8531	2930
17	10.00	0.4244	113.39	7837	8813	7539	2599
18	10.00	0.4244	81.71	95	111	98	34
19	0.22	1.1828	34.66	5546	4398	3987	3703
20	0.00	1.1677	60.02	2868	2759	2047	1876
21	0.00	0.5316	76.10	1048	2110	1208	504
22	0.00	0.5316	1.64	136	279	259	108

Slice No.	-- Surcharge loads --		Water load on submerged ground	
	vertical load kN/m	horizontal load kN/m	vertical kN/m	horizontal kN/m
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	34	0	0	0
14	47	0	0	0
15	78	0	0	0
16	180	0	0	0
17	156	0	0	0
18	2	0	0	0
19	0	0	0	0
20	0	0	0	0
21	0	0	0	0
22	0	0	0	0

Limited Operation Demonstration Version  
 Program: SLOPE Version 12R.01 Revision A09.B06.R31  
 Licensed from GEOSOLVE  
 Run ID: Demo9a  
 Gravity retaining wall  
 Overall stability

| Sheet No.  
 |  
 | Job No.  
 | Made by :  
 | Date:10-08-2005  
 | Checked :

Units: kN,m



## APPENDIX F

### PARTIAL FACTORS OF SAFETY

#### F.1 DEFINITION OF FACTOR OF SAFETY

Modern codes of practice use partial factors on the separate components of a structure. In slope stability analysis and reinforced earth design, overall stability is ensured by applying partial factors of safety, separately, to the soil and reinforcement strengths, as well as a possible overall factor of safety on the balance between disturbing and restoring forces. The equation for factor of safety is of the form

$$f = \frac{R_{\text{soil}}/f_{\text{soil}} + R_{\text{reinf}}}{D_{\text{wt}} \cdot f_{\text{wt}} + D_{\text{load}} \cdot f_{\text{load}}} \quad (\text{F.1})$$

Where

$D_{\text{wt}}$  = Disturbing force due to soil weight

$f_{\text{wt}}$  = Partial factor of safety on soil weight

$D_{\text{load}}$  = Disturbing force due to surcharge loads

$f_{\text{load}}$  = Partial factor of safety on surcharge loads

$R_{\text{soil}}$  = Restoring force due to soil strength

$f_{\text{soil}}$  = Partial factor of safety on soil strength

$R_{\text{reinf}}$  = Restoring force due to reinforcement (factored)

$f$  = Overall factor of safety on soil + reinforcement

#### Definition of factor of safety for load factor calculation

When calculating the factor of safety on surcharge loads,  $f_q$  is defined as follows:

$$f_q = \frac{R_{\text{soil}}/f_{\text{soil}} + R_{\text{reinf}} - D_{\text{wt}} \cdot f_{\text{wt}}}{D_{\text{load}} \cdot f_{\text{load}}} \quad (\text{F.2})$$

### F.2 PARAMETERS REQUIRED BY SLOPE

#### F.2.1 Soil weight, $D_{\text{wt}}$

Characteristic (i.e. best estimates, unfactored) soil densities should be entered in the data. If a partial factor,  $f_{\text{wt}}$ , is required, this value is entered separately (see below).



**F.2.2 Partial factor of safety on soil weight,  $f_{wt}$** 

Values of partial factors on soil densities should be obtained from relevant codes of practice. The program applies the same factor to both bulk densities (above and below the water table).

**F.2.3 Surcharge loads,  $D_{load}$** 

Characteristic (i.e. best estimates, unfactored) loads should be entered in the data. If a partial factor,  $f_{load}$ , is required, this value is entered separately (see below). To conform with all the requirements of some design codes, it may be necessary to carry out more than one analysis/design with various load combinations.

If different load factors are required on different components of the surcharge load then it will be necessary to enter partially factored loads in the data. The Partial factor,  $f_{load}$  (below) should then be set to 1.

**F.2.4 Partial factor of safety on surcharge loads,  $f_{load}$** 

Values of partial factors on loads should be obtained from relevant codes of practice.

**F.2.5 Soil strengths,  $R_{soil}$** 

Characteristic (or reasonably conservative) strengths should be entered in the data. If a partial factor,  $f_{soil}$ , is required for reinforcement or bearing capacity analysis/design, this value is entered separately (see below).

**F.2.6 Partial factor of safety on soil strength,  $f_{soil}$** 

Values of partial factors on soil strength generally lie between 1.0 and 1.5 depending on the type of strength parameters used e.g. Peak strengths, Residual strengths or Critical State strengths.

**F.2.7 Reinforcement force,  $R_{reinf}$** 

The contribution to stability of a layer of reinforcement is limited by:

1. Its tensile strength,  $T_{reinf}$
2. Its pull-out resistance due to friction,  $\phi_{pull}$ ,  
and cohesion,  $c_{pull}$

Each component of reinforcement resistance is subject to its own factor of safety. Characteristic values of strength,  $f_{\text{pull}}$  and  $c_{\text{pull}}$  should be entered in the data. If partial factors,  $f_{\text{tens}}$  and  $f_{\text{pull}}$ , are required, their values are entered separately (see below).

### **F.2.8 Partial factor of safety on reinforcement strength, $f_{\text{tens}}$**

See Section 11.3.1 for the definition and advice on this parameter.

### **F.2.9 Partial factors of safety on soil-reinforcement interaction.**

Two partial factors are defined for soil-reinforcement interaction.

- a) Partial factor on pull-out resistance,  $f_{\text{pull}}$
- b) Partial factor on direct sliding resistance,  $f_{\text{slide}}$

These factors are defined and discussed in Sections 11.3.2. and 11.3.3 respectively.

### **F.2.10 Overall design factor of safety on soil + reinforcement, $f_{\text{des}}$**

This parameter is only required for reinforced soil **design** as discussed in Section 11.4.3. During the design process the program evaluates the overall factor of safety,  $f$ , (Equation F.1) for a wide range of mechanisms. The program ensures that sufficient reinforcement is provided to guarantee that the factor of safety for any mechanism is never less than  $f_{\text{des}}$ . Suitable values of  $f_{\text{des}}$  are suggested in Section 11.4.3.

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Problems of soil mechanics and construction on soft clays.  
State of the art report. Proc.8th Int.Conf.SMFE.

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Code of practice for strengthened / reinforced soils and other fills.  
British Standards Institution

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**Janbu, N., L.Bjerrum and B.Kjaernsli (1956)**

Stability calculations for fillings, cuts and natural slopes.  
Norwegian Geotechnical Institute. Publ.No.16.

**Spencer, E. (1967)**

A method of analysis of the stability of embankments ensuring  
parallel interslice forces.  
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Use of computers for slope stability analysis.  
Proc. ASCE, Vol.93 SM4. pp.475-498.

## NOTATION

$A_{\text{nail}}$	Empirical design factor for nails in cohesionless soil as defined in BS 8081
$c$	Soil cohesion
$c_{\text{nail}}$	Undrained cohesion of the soil in which a nail is installed
$c_o$	Undrained cohesion at datum elevation $y_o$
$c_u$	Undrained cohesion of cohesive soil
$c_u/p'$	Ratio of undrained cohesion to effective overburden pressure for normally consolidated soil
$c'$	Drained cohesion of cohesive soil
$c_{\text{pull}}$	Adhesion between reinforcement and soil for pull-out
$c_{\text{slide}}$	$= c_{\text{pull}} =$ Adhesion between reinforcement and soil for direct sliding and pull-out
$dc/dy$	Rate of increase of cohesion with depth
$D_{\text{nail}}$	Effective nail diameter
$E_h$	Horizontal acceleration factor
$E_v$	Vertical acceleration factor
$f$ (F)	Overall factor of safety on soil (+ reinforcement) strength
$f_q$	Factor of safety on surcharge loads (calculated)
$f_{\text{load}}$	Partial factor of safety on surcharge loads
$f_{\text{soil}}$	Partial factor of safety on soil strength
$f_{\text{wt}}$	Partial factor of safety on soil weight
$f_{\text{pull}}$	Partial factor of safety on pull-out resistance
$f_{\text{slide}}$	Partial factor of safety on direct sliding resistance
$f_{\text{tens}}$	Partial factor of safety on tensile strength of reinforcement
$f_{\text{des}}$	Overall design factor of safety on soil + reinforcement strength
$h_A$	Piezometric head at point A
$r_u$	Pore pressure ratio
$S$	Ratio of width to spacing of reinforcements
$u$	Pore pressure
$u_w$	Pore water pressure
$u_A$	Water pressure at Point A
$x_t$	X coordinate of toe of slope
$y$	Elevation
$y_A$	Elevation of Point A
$y_o$	Datum elevation at which $c_o$ occurs

## NOTATION (continued)

$\alpha_{\text{nail}}$	Adhesion (alpha) factor for nails in cohesive soil as defined in BS 8081 (Ground Anchors)
$\alpha_{\text{int}}$	Soil-reinforcement Interaction Coefficient
$\alpha$	Inclination of slip surface to the horizontal (Figure 8a)
$\alpha$	Wedge angle in two and three part wedges (Figure 13a)
$\beta$	Base angle (Three part wedges)
$\varepsilon$	Exit angle (Three part wedges)
$\gamma$	Unit weight of soil
$\gamma_w$	Unit weight of water
$\Delta R$	Incremental radius
$\sigma_v$	Vertical total stress
$\sigma$	Total stress
$\sigma'$	Effective stress
$\sigma'_v$	Vertical effective stress
$\mu_{\text{nail}}$	Coefficient of friction between nail and soil
$\mu_{\text{pull}}$	Coefficient of friction between reinforcement and soil for pull-out
$\mu_{\text{slide}}$	Coefficient of friction between reinforcement and soil for direct sliding
$\phi$	Angle of soil friction
$\phi'$	Effective angle of soil friction
$\phi_m$	Mobilised angle of soil friction

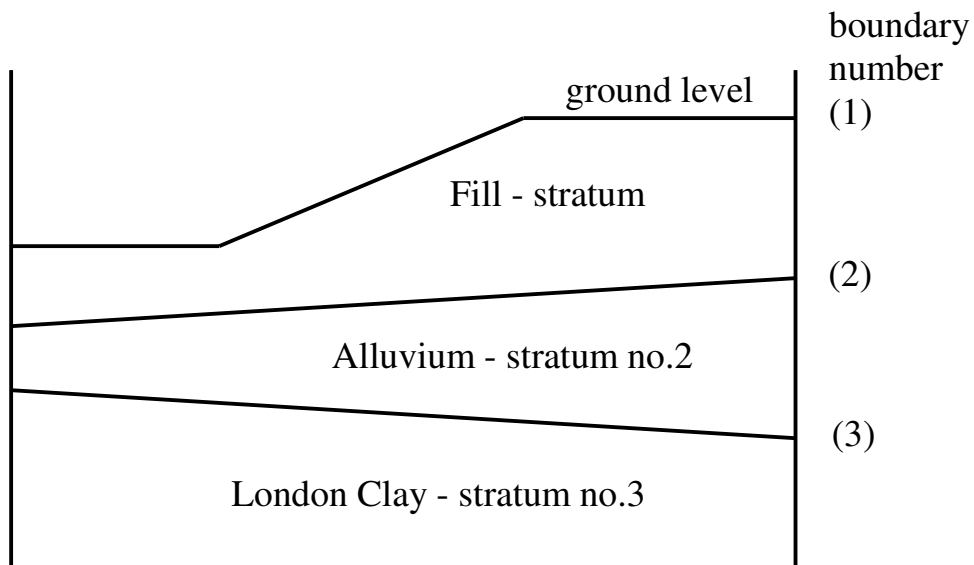


Figure 1a. Numbering convention for soil strata

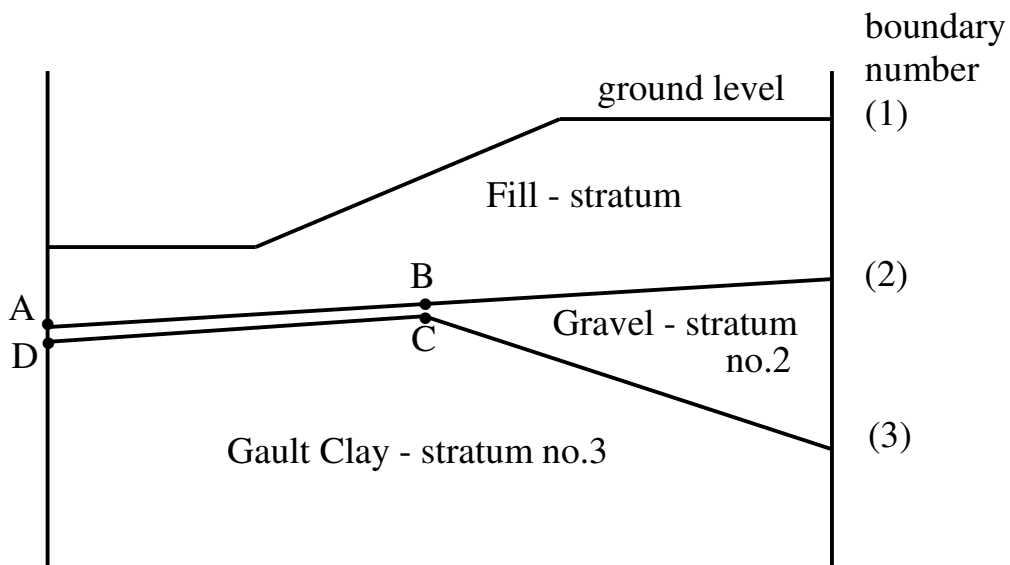


Figure 1b. Representation of a discontinuous stratum

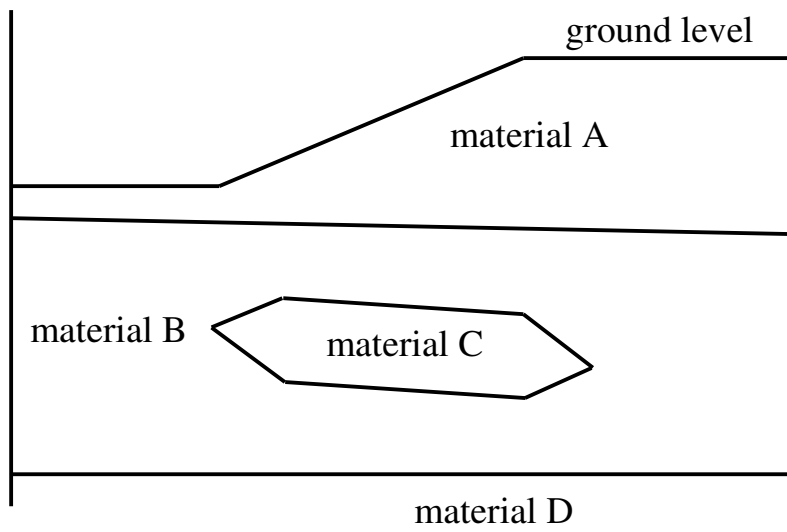


Figure 2a.

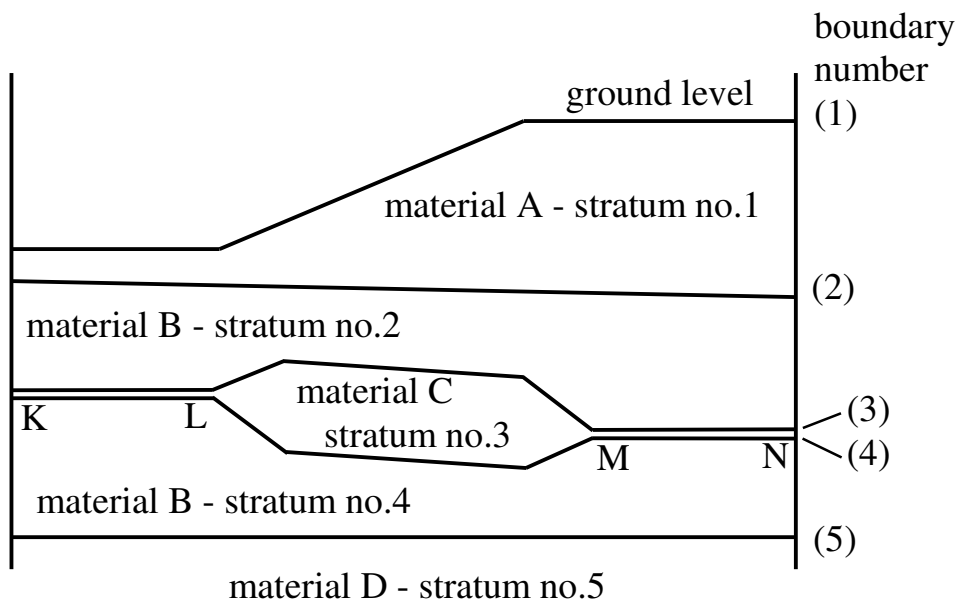


Figure 2b. Representation of a lenticular soil mass

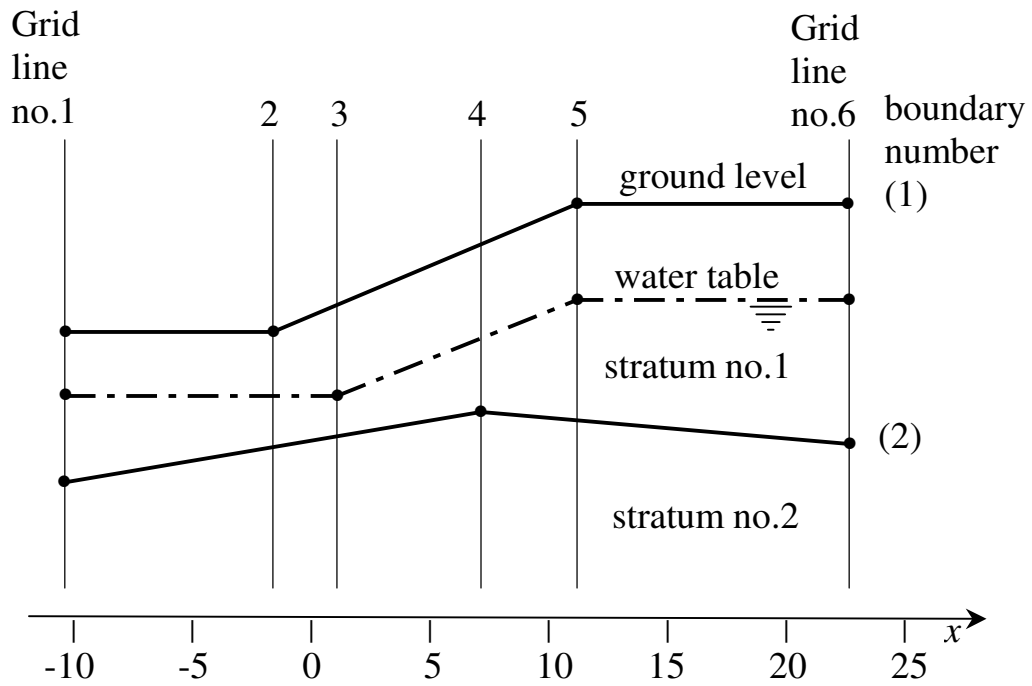


Figure 3a. Positioning of grid lines at changes in gradient of strata boundaries and water table

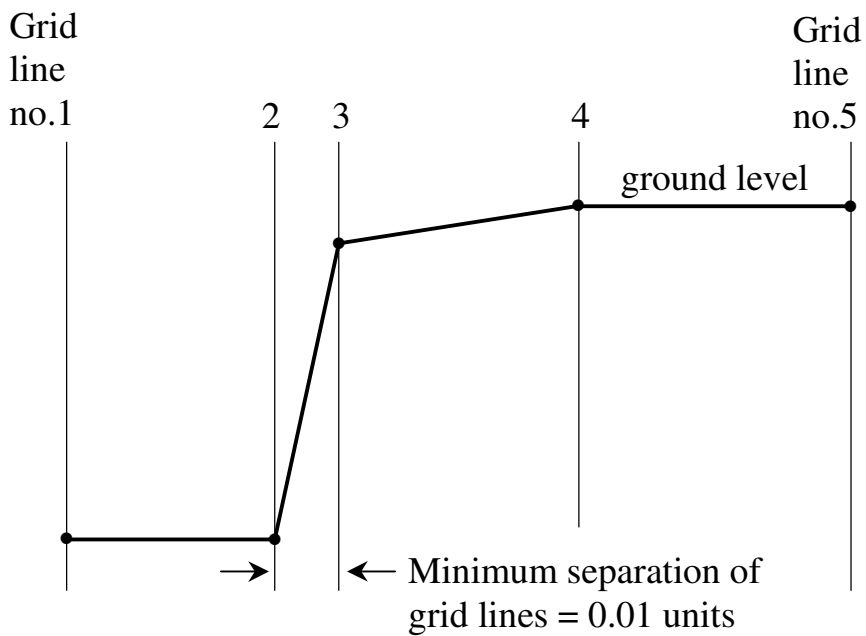
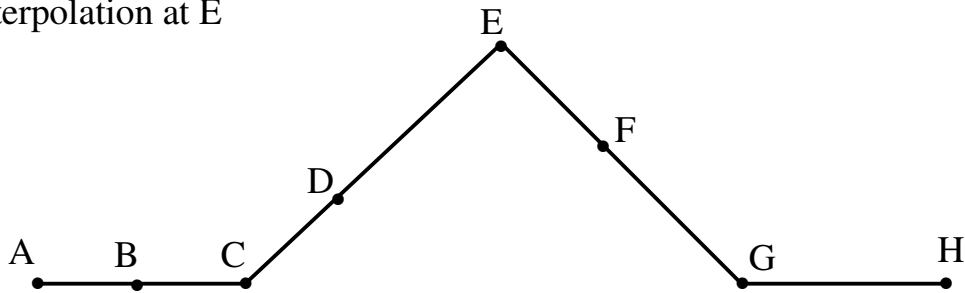


Figure 3b. Representation of a vertical cut by a line of very steep gradient



Interpolation at E



Results in this profile

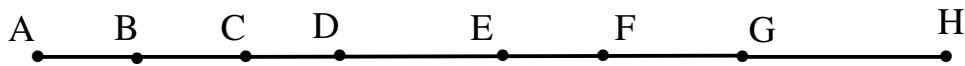


Figure 3c. Interpolation to remove a bump in a soil stratum

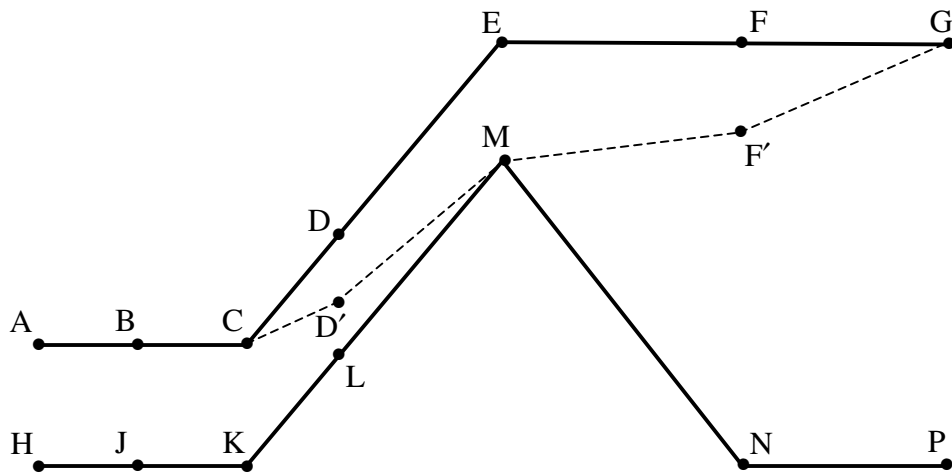


Figure 3d. Interpolation restricted by a neighbouring stratum

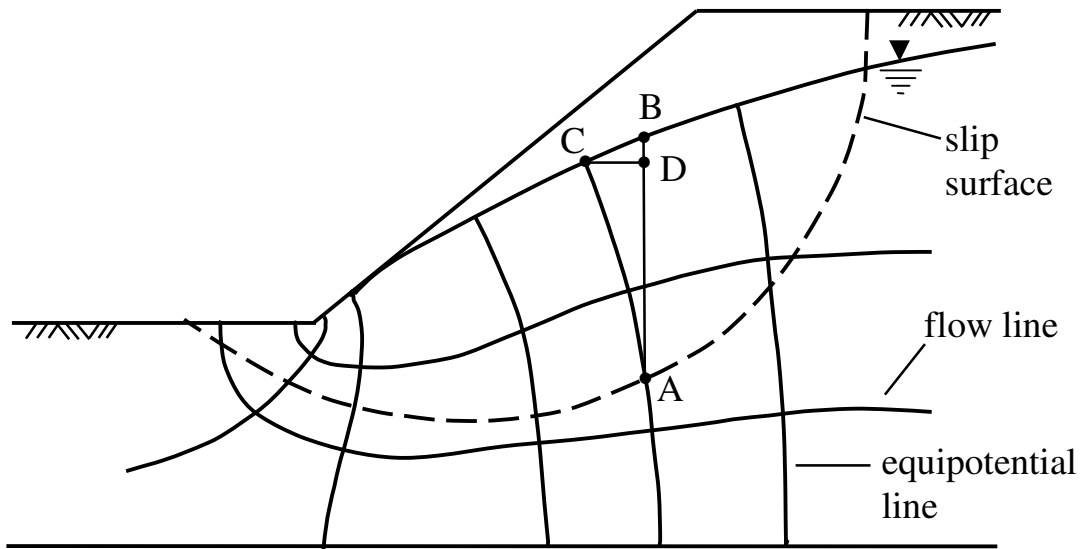


Figure 4a. Error due to assumption of hydrostatic pore pressure distribution

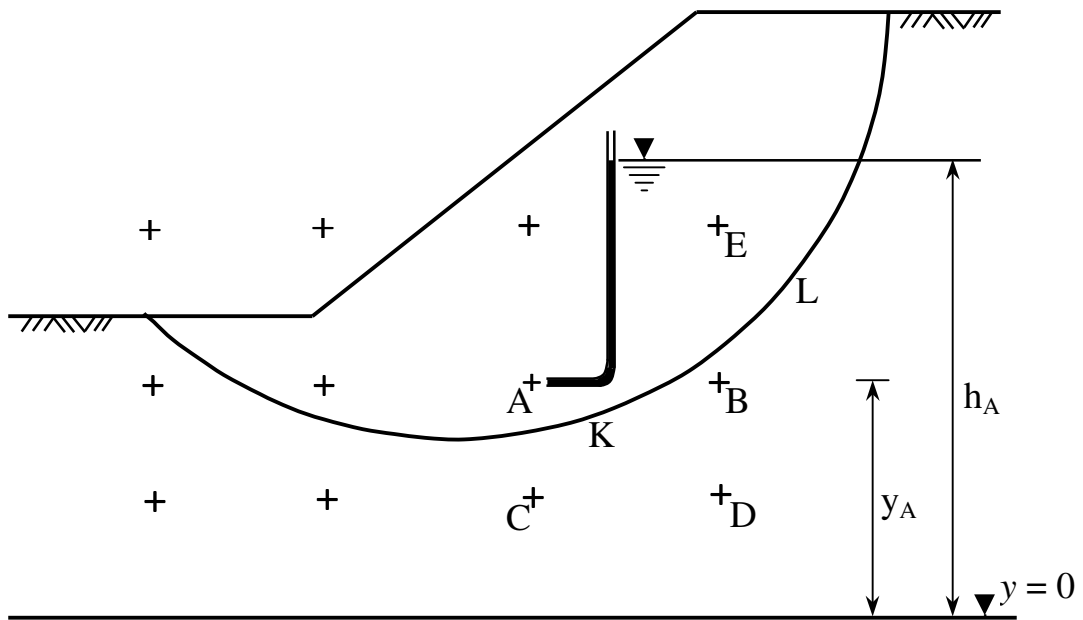


Figure 4b. Grid of pore pressure points

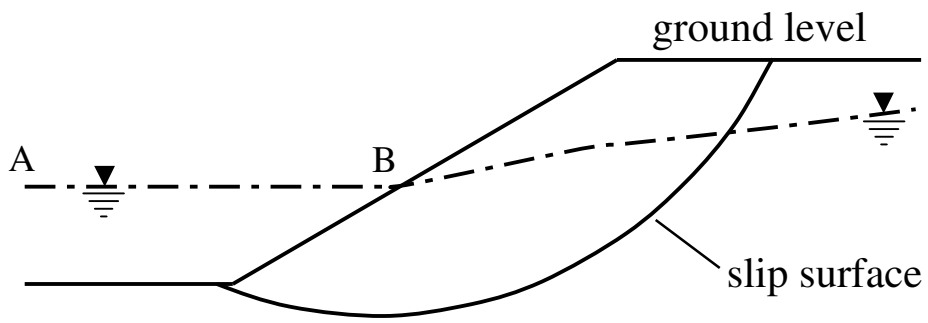


Figure 5a. Submerged ground : static water level

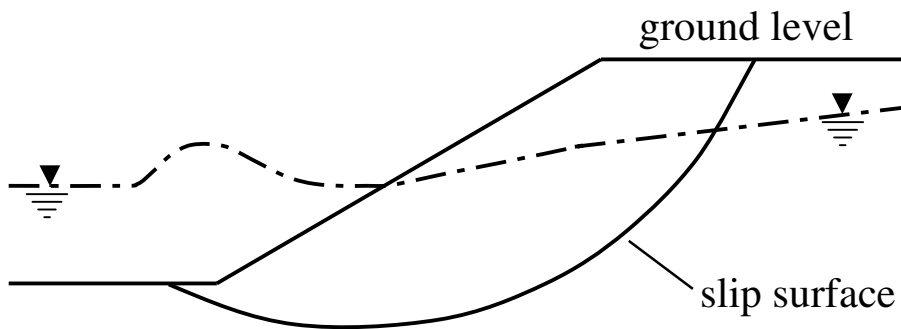


Figure 5b. Submerged ground : wave condition

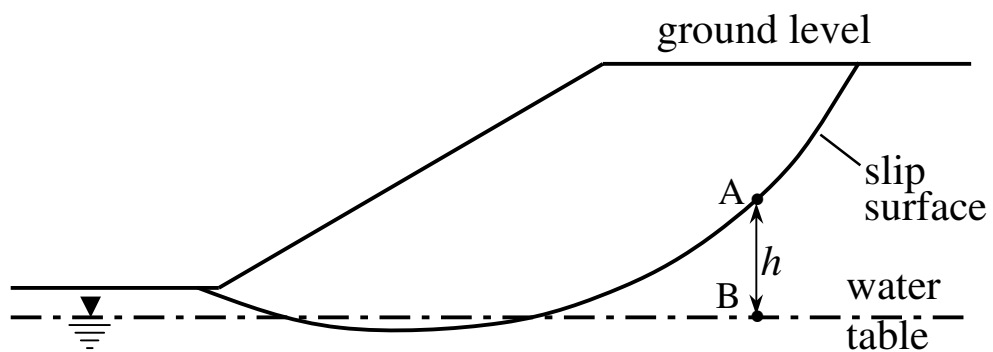


Figure 5c. Soil suction

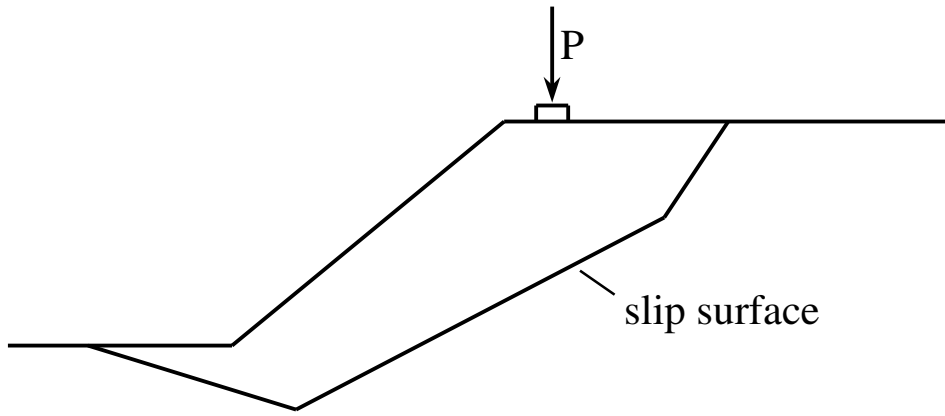


Figure 6a. Line load,  $P$  per unit length

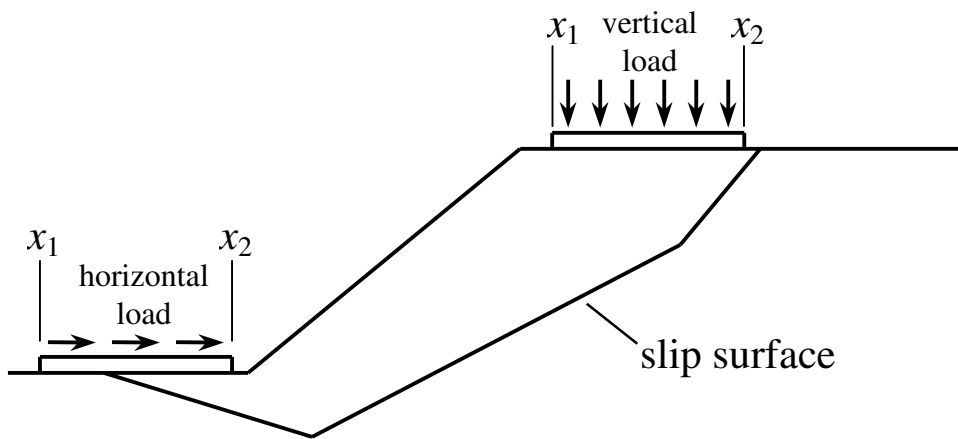


Figure 6b. Distributed surface loads

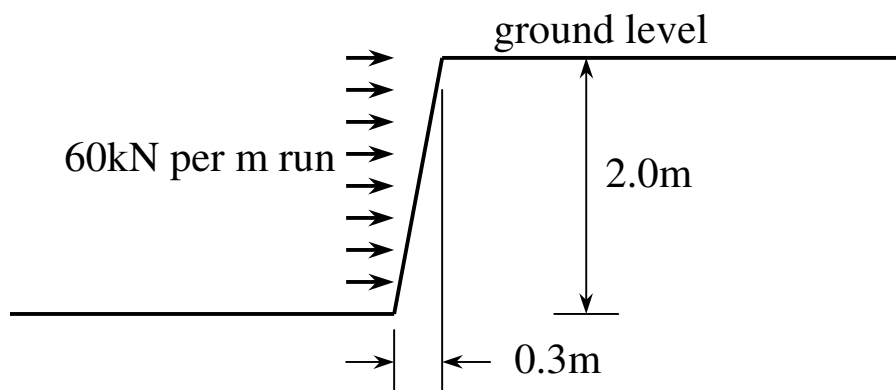


Figure 6c. Horizontal load on a sloping surface

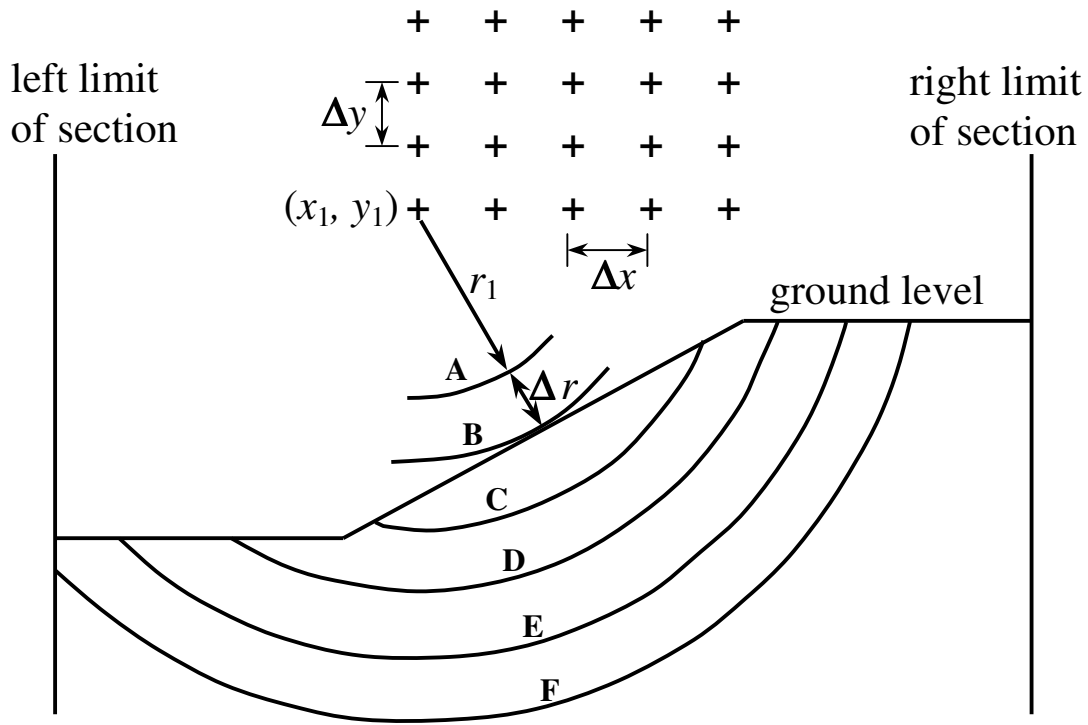


Figure 7a. Grid of centres and increment of radius

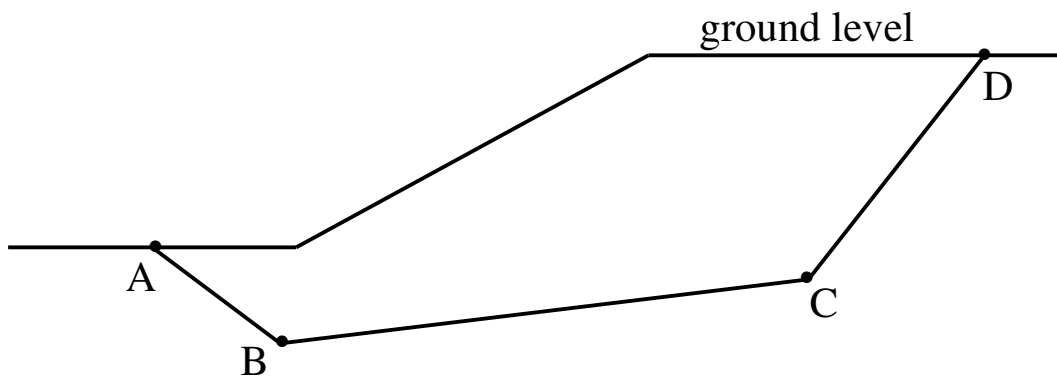


Figure 7b. Non-circular slip surface

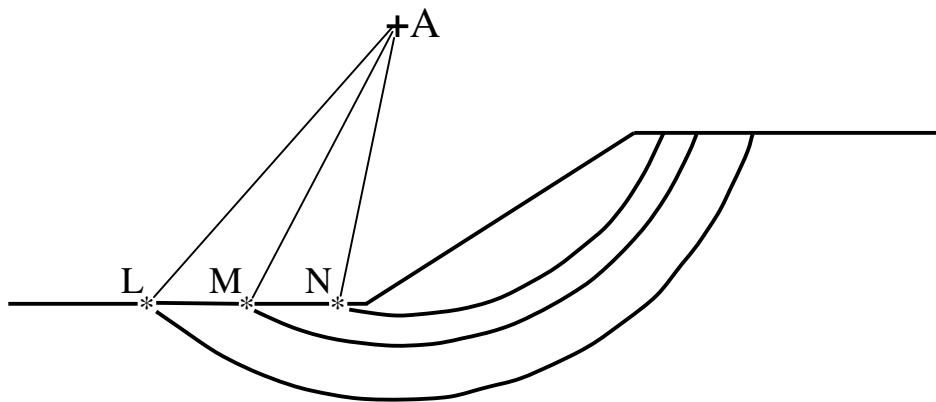


Figure 7c. Common point(s) for all circles to pass through

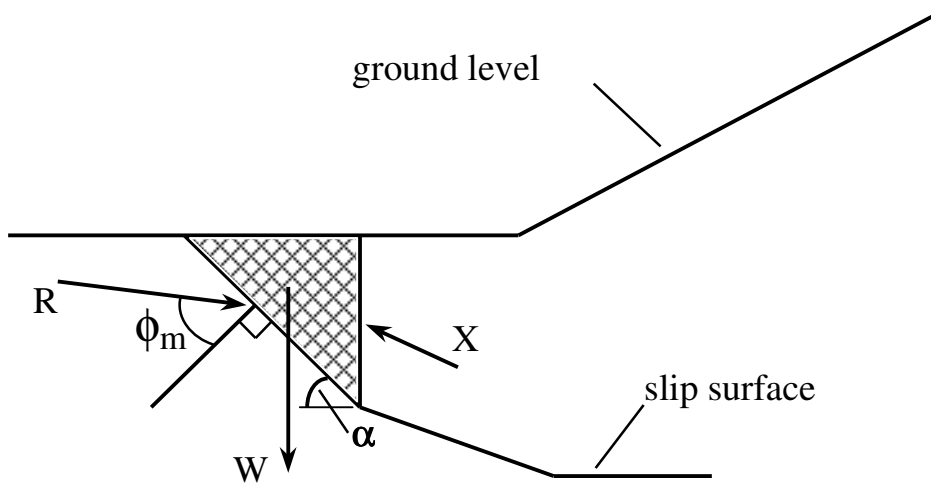


Figure 8a. The interlock problem at the toe of a slope

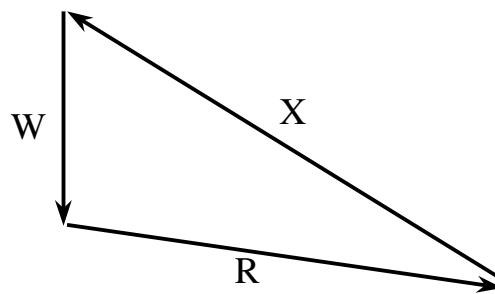


Figure 8b. Force diagram for interlock problem

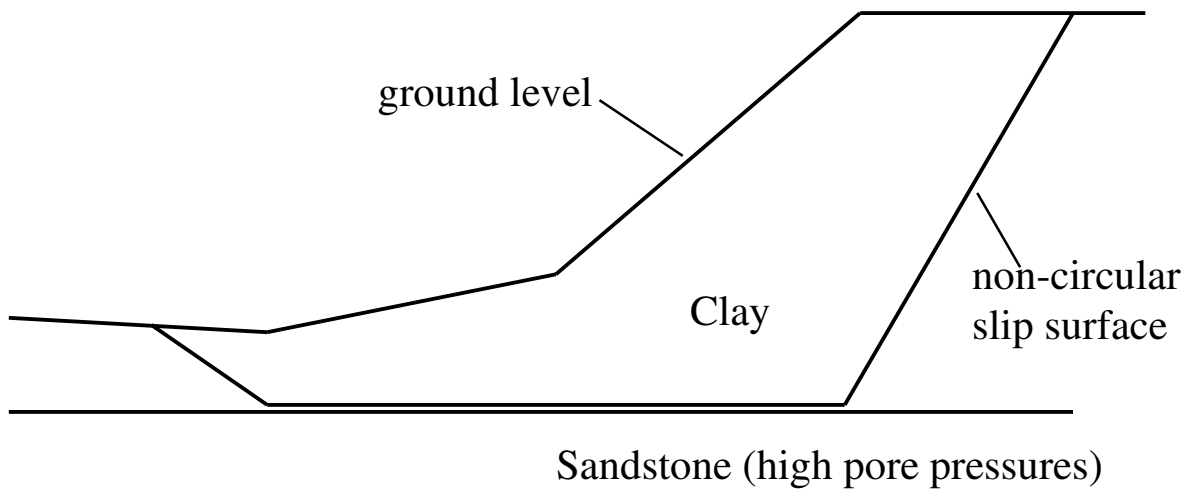


Figure 9a. Non-circular slip surface in non-homogeneous strata

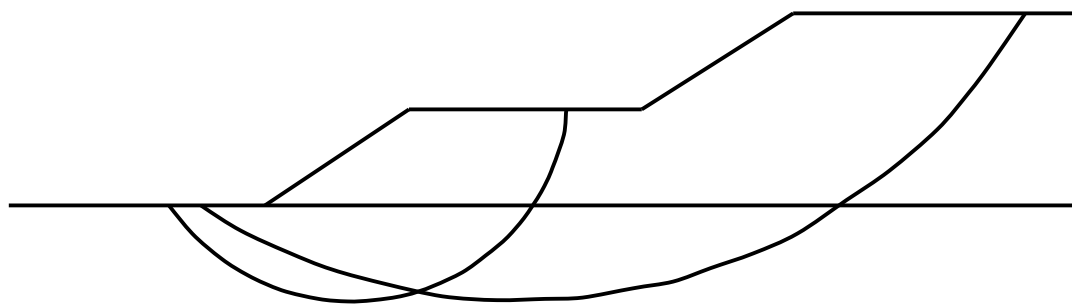


Figure 9b. Two distinct modes of failure for an embankment with berms

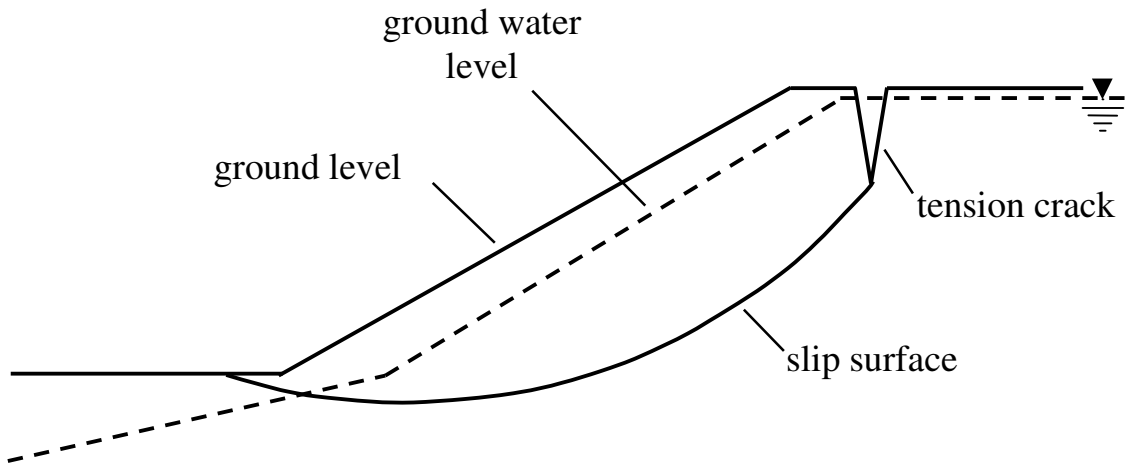


Figure 10a. Modelling a tension crack

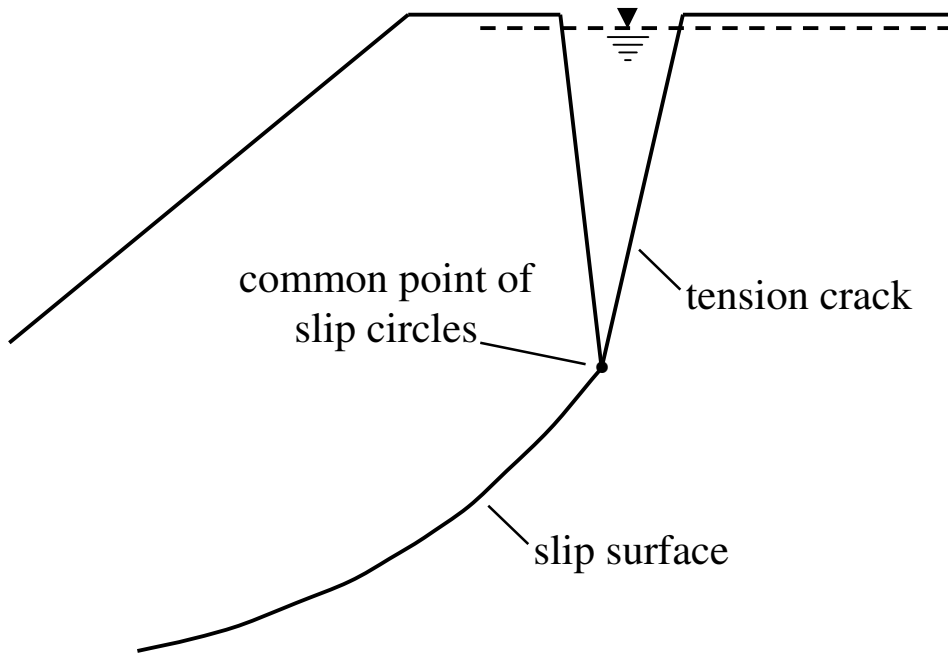
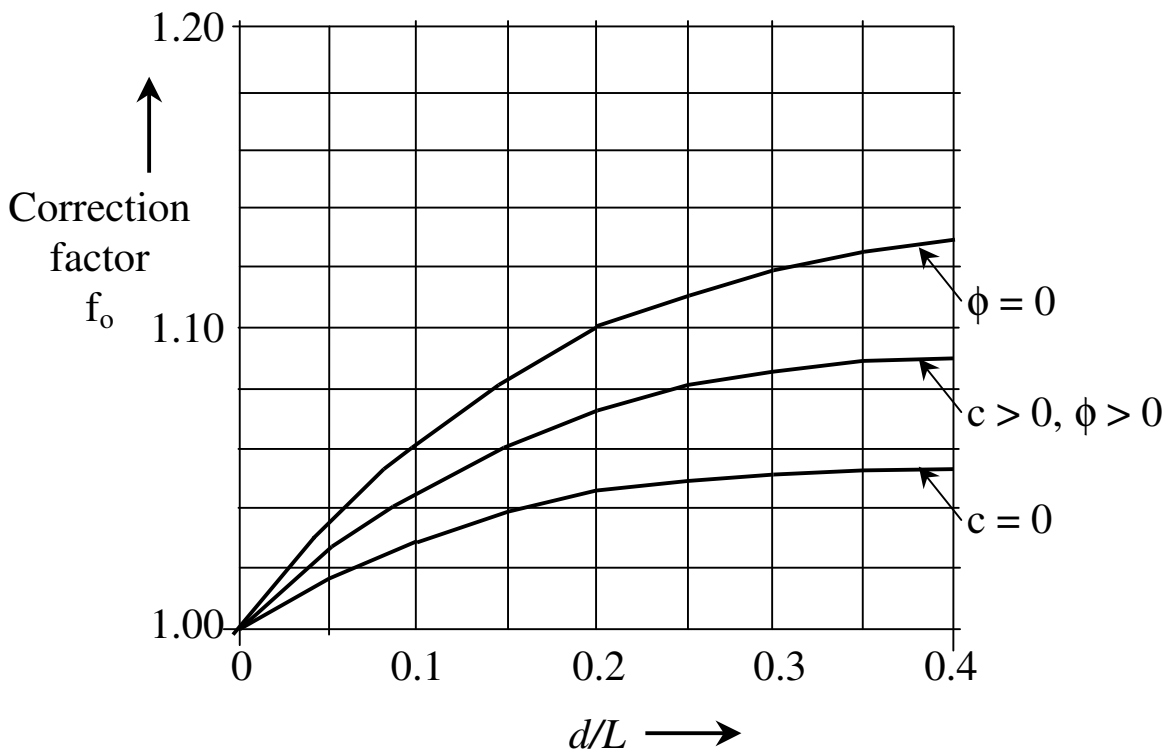
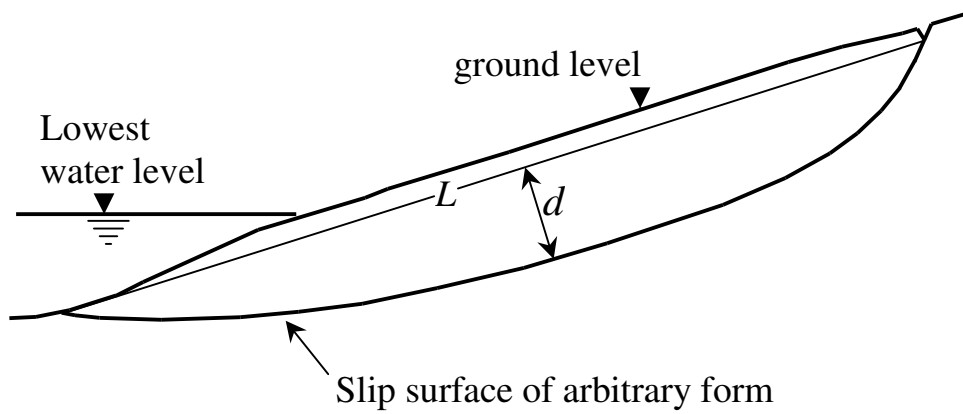


Figure 10b. Detail of a tension crack





Correction factor,  $f_o$ , for Janbu's method

After Janbu, Bjerrum and Kjaernsli (1956)

Figure 11

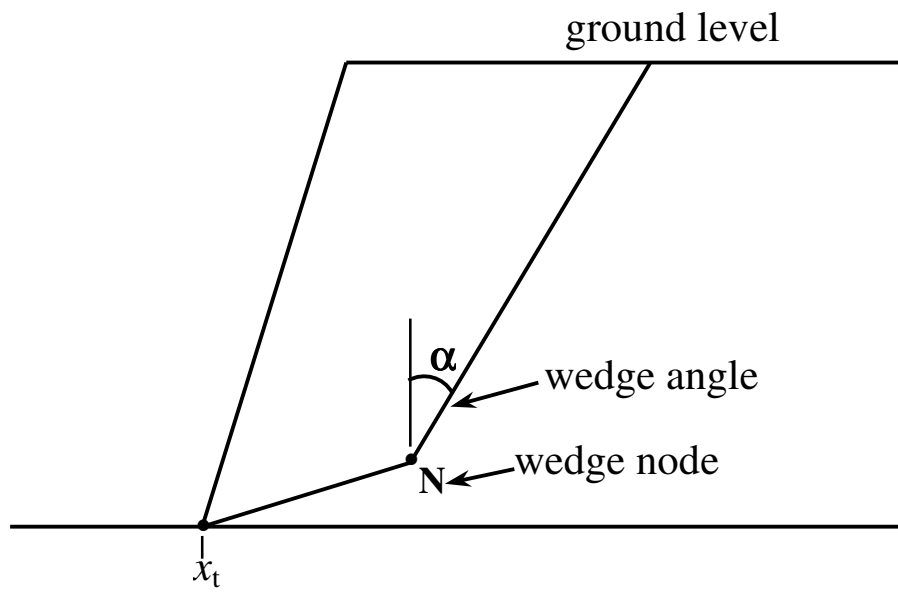


Figure 13a. Two part wedge definition

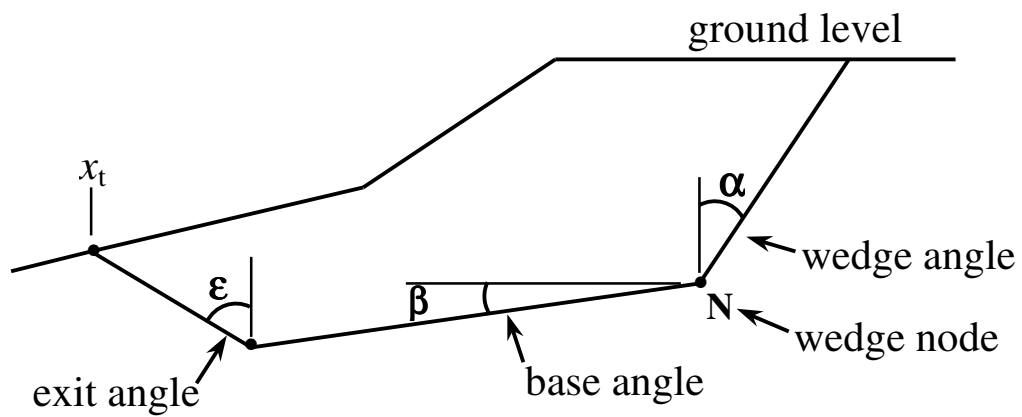


Figure 13b. Three part wedge definition

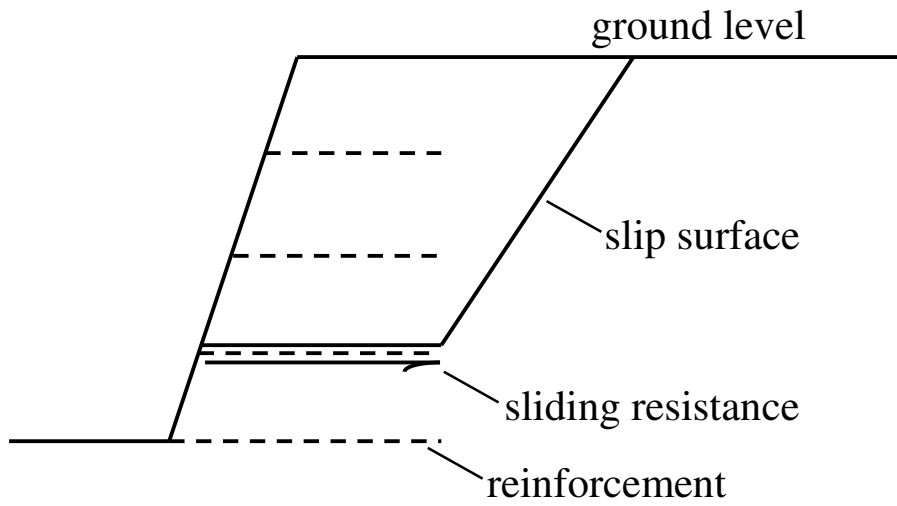


Figure 14a. Direct sliding failure on reinforcement

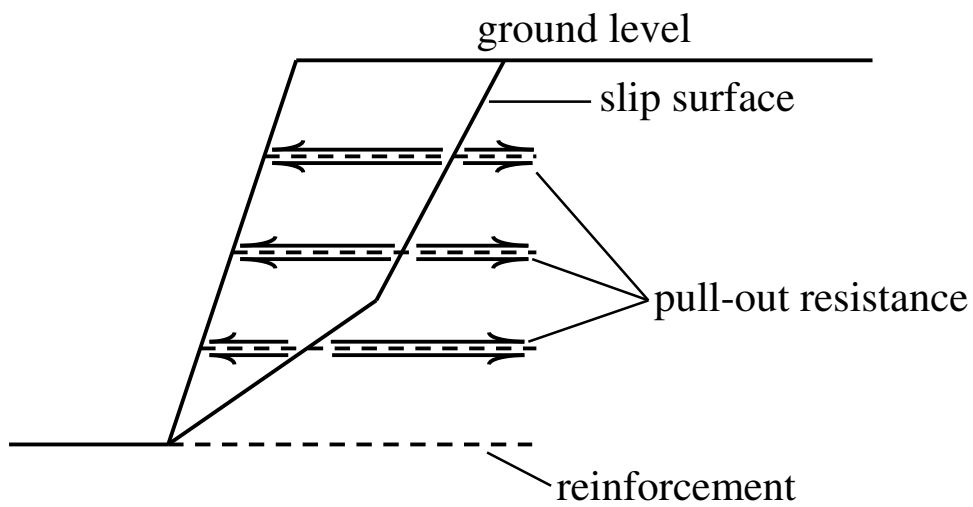


Figure 14b. Pull-out failure of reinforcement

**SLOPE Version 12R.01 Revision A09.B06.R31** Limited Operation Demonstration Version

File Import Edit View Format Analysis Help

Path = C:\... \Current\SLOPE\TestData File = Demo9a.dat  
Data last modified 10-08-2005 20:48

Gravity retaining wall  
Overall stability

Data input  Analyse  View Results  Report

Titles Strata Soil types GWL Piezo grid Surcharge Slip surface FoS options Reinf. props. Reinf. design Output

**Soil properties**

No.	Soil type Description	below GWL kN/m3	above GWL kN/m3	C kN/m2	Phi (deg)	dC/dy kN/m2/m	datum for C
1	Silty sand	20.00	19.00	0.00	28.00	Piezometric surface no. 1	
2	Thames gravel	25.00	25.00	0.00	50.00	0	0.00
3	Gravity wall	25.00	25.00	1000.0	0.00	0	0.00
4	London Clay	20.00	20.00	10.00	23.00	0	0.00
5	Chalk	22.00	22.00	300.00	20.00	0	0.00

No Data Errors or Warnings

Options

Scale = 1 : 2241

Undo

Figure 12a SLOPE Desktop - Data Input mode

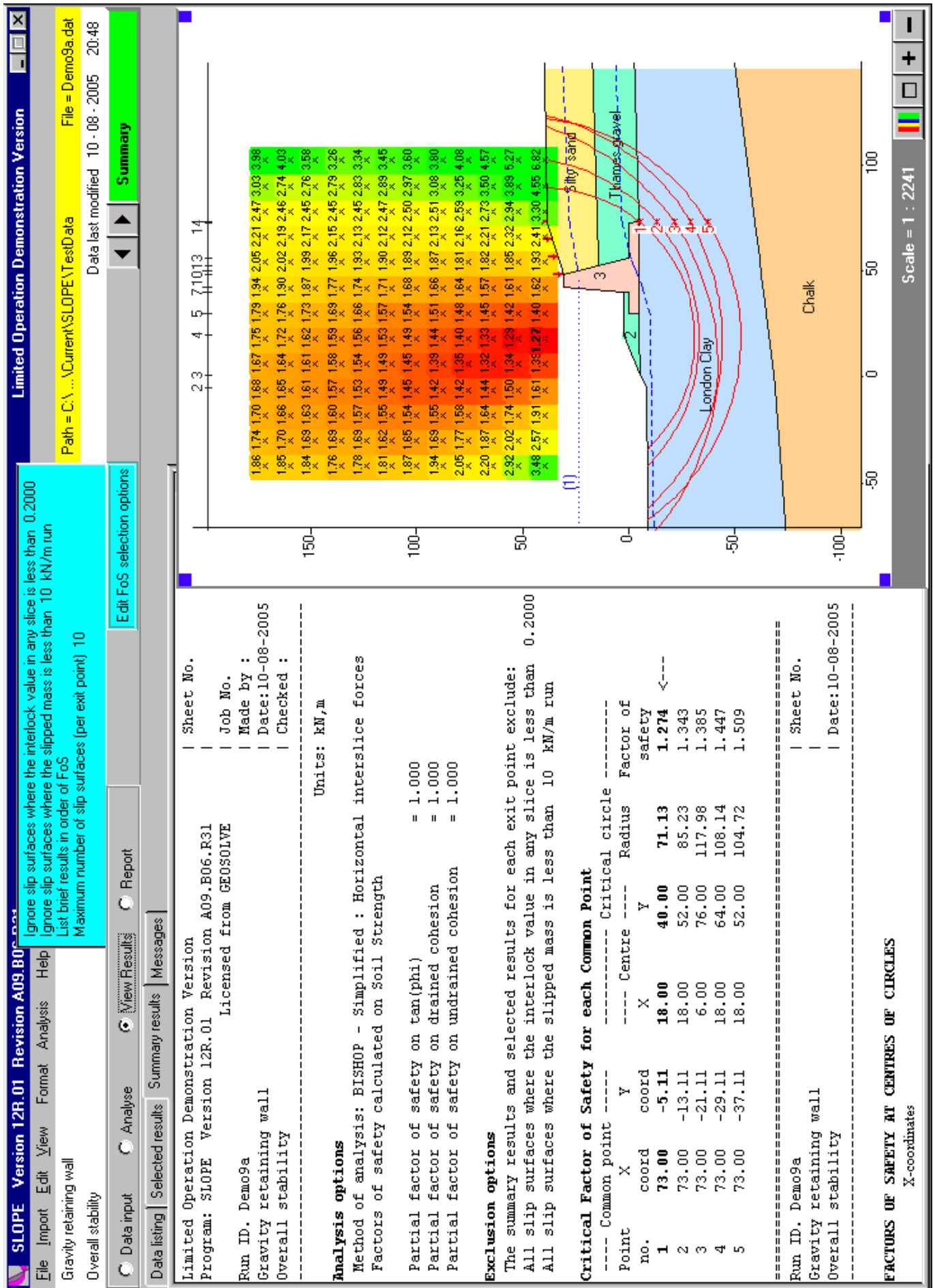


Figure 12b SLOPE Desktop - View Results mode