CLOVER
TECHNOLOGY

GALENA®

Slope Stability Analysis System

Users' Guide

Version 4.0

For Windows 95/98/Me and Windows NT4/2000/XP

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GALENA®

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SUMMARY

GALENA is designed to be a simple, user-friendly yet very powerful, slope stability software system. It was originally developed to satisfy the requirements of BHP (now known as BHP Billiton) geotechnical engineers who realised there were many problems with other slope stability analysis software systems available. Geotechnical engineering very rarely gives one unique answer and extensive parametric studies are often required before realistic results are obtained. ***GALENA*** enables such parametric studies to be undertaken quickly and easily.

The ***GALENA*** system considers slope stability problems as they are largely encountered in the field. That is, the overall geology generally remains the same; it is the slope surface that requires change in many situations. In ***GALENA,*** the *overall geology is defined* for the model, including the material properties. The defined slope surface then cuts through this model, as a slope would be excavated in the real world. Material above the slope surface is ignored since this has been removed or mined out. In this way, ***GALENA*** enables a large number of analyses to be undertaken without the need to redefine the model each time.

In addition, a range of different constraints and methods of analysis can then be used on that same model. This enables parametric studies to be undertaken very easily. The program is structured such that parameters can be defined or input in almost any sequence, provided they follow basic rules as outlined in this Users' Guide - for example the slope surface *need not be defined* before the material profiles.

GALENA incorporates the Bishop Simplified, the Spencer-Wright and the Sarma methods of analysis to determine the stability of slopes and excavations. The Bishop method is used to determine the stability of circular failure surfaces, the Spencer-Wright method is applicable for circular and non-circular failure surfaces, and the Sarma method is used for problems where non-vertical slices are required, or is used for more complex stability problems.

It is possible to analyse multi-layered slopes with tension cracks, earthquake forces, externally distributed loads and forces, and water pressures from within or above the slope (e.g. dams and river banks) including phreatic surfaces and piezometric pressures. ***GALENA*** incorporates various techniques for locating the critical failure surface with user-supplied restraints. Back analyses can also be performed to obtain critical material strength parameters from known or assumed failure surfaces, and probability analyses performed to gauge the likelihood of Factors of Safety being below values of interest, based on expected material property variations.

Either effective or total stresses may be used on any material layer. For the total stress case, the increase in undrained shear strength with depth can be simulated using Skempton's relationship by simply entering the value of the plasticity index for that material.

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GALENA produces printed results and graphical images. The slope cross-section and the critical or specified failure surface are imaged along with the resulting Factor of Safety.

GALENA enables back analyses to be easily performed and curves of the critical relationships between material strength parameters (cohesion and angle of shearing resistance) are produced.

Probabilistic analysis can be readily undertaken using either defined material properties, or defined mean values, and standard deviation for the production of density and distribution plots.

GALENA allows shear strength to be defined using traditional c and phi values, the Hoek-Brown (1983) failure criterion (m, s and UCS), or with shear/normal data from curves of any shape.

GALENA was developed by geotechnical engineers to be a system primarily for practising engineers rather than for researchers, although many researchers now feel at home with ***GALENA*** for their slope stability studies. The ***GALENA*** system has been field-tested on a wide variety of earth and rock slopes, dams and cuttings and has proved to be reliable, accurate and easy to use, although you should note the Limited Warranty that applies to this software.

Finally, we hope that you are able to undertake some interesting slope stability engineering with ***GALENA***, and now more quickly, more easily and more efficiently with this latest release of ***GALENA***. Any comments on how the system could be improved further would be welcomed, and we may be able to include your suggestions in a future release.

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2.1 Commentary

Geotechnical engineering is rarely an exact science and a considerable amount of engineering judgement is necessary for many practical geotechnical problems. Additional information on the location of the failure surface, or on the physical properties, or on the geological structure, would almost always be desirable, but time and financial constraints necessitate that the geotechnical engineer use his or her judgement about many of these parameters.

An issue that has been fiercely debated in the geotechnical literature, is which slope stability method is correct? This debate focuses on such questions as:

- Does it consider force equilibrium?
- Does it consider moment equilibrium?
- Does it have a local or global factor of safety?
- Does it consider inter-slice shear strengths and forces?
- Does it allow non-vertical slices?
- Does it allow for progressive failure?
- Is it kinematically admissible?

Quoting Factor of Safety values to three or more decimal places, and then further comparing these limiting equilibrium method results to finite element analyses of the same problem to determine a “right answer” is ***inappropriate*** for most geotechnical applications.

Firstly, even finite element analyses using the most sophisticated modelling techniques, do not necessarily produce the "right" answer, and for slope stability analyses in complex geology could, in fact, produce misleading results. Secondly, Factor of Safety values should not be quoted to high levels of accuracy since the input parameters will rarely be known with sufficient accuracy to warrant this level of definition for the Factor of Safety.

In summary, the stability of any slope is independent of the method of stability analysis. Some methods of slope stability analysis are better suited to some problems than others, and in this respect, the geotechnical engineer should choose the method of analysis carefully. No one method is ideally suited to all problems and you should be aware of the advantages and limitations of different methods before using ***GALENA*** (refer to the References for further information on each of the methods of slope stability analysis).

In a large number of cases, the error range of the input parameters is likely to exceed the difference in "accuracy" between the various possible analytical techniques.

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2.2 Methods Of Analysis

GALENA incorporates three different methods of slope stability analysis. These are:

(i) BISHOP SIMPLIFIED METHOD - suitable for circular failure surfaces.

(ii) SPENCER-WRIGHT METHOD - suitable for circular and non-circular failure surfaces.

(iii) SARMA METHOD - suitable for more complex problems particularly where non-vertical slice boundaries (such as faults or discontinuities) are significant.

In most instances, slope stability problems can be analysed with one of the above methods. However, for complex slope stability problems where in-situ stresses are significant, it may be more appropriate to use a stress analysis method such as finite element or finite difference etc. Nevertheless, *GALENA* will provide rapid answers for most slope stability problems and it has some features that are designed specifically for the practising geotechnical engineer, which are detailed within this Users' Guide.

2.3 Searching

One of the other problems, which frequently occupy much discussion in the geotechnical literature, is how to search for the failure surface with the minimum Factor of Safety or with the greatest probability of failure. BHP Engineering geotechnical staff investigated the various methods of searching including simplex methods, and concluded that automatic computer searching can be misleading. The reason that it can be misleading is simply that geotechnical engineers are not really interested in the failure surface with the minimum Factor of Safety.

In some homogenous slopes, the minimum Factor of Safety is given by a very small failure circle in the upper part of the slope near the crest. This failure surface is so small that it is not relevant for practical problems. Therefore BHP Engineering introduced, through *GALENA* and its predecessors, the concept of "restraints" so that geotechnical engineers could focus their investigations on failure surfaces that were meaningful. Automatic computer searching does not allow this to occur.

In addition, for practical problems, failures nearly always pass through, or near to, the toe of the slope. *GALENA* therefore also introduced the concept of X-LEFT, X-RIGHT and RADIUS rather than XC, YC and R (as most other programs do) and this rapidly enables you to define and explore the area of interest. (The XC, YC and R option is retained to allow you to make comparisons with existing analyses, etc., but we strongly recommend the use of X-LEFT, X-RIGHT and RADIUS.) Information regarding the use of Restraints is provided in on-line Help and within this Users' Guide and it will become obvious that the relevant minimum Factor of Safety values can be determined very rapidly with *GALENA*.

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2.4 BackAnalysis

Backanalysis is a subject that is also mentioned extensively in the literature but few programs have a specific facility to undertake such. ***GALENA*** has a specific backanalysis capability that can be used for both backanalysis of past failures and the design of existing slopes. Backanalysis answers the common question of 'What strength is required?' rather than 'What is the stability?' of a given slope. Further information on backanalysis is provided within this Users' Guide.

2.5 Probability Analysis

Over the past fifteen years or so, probability concepts have been applied to geotechnical problems to try and overcome the difficulties of using engineering judgement and to take some of the guesswork out of the natural variability of geological materials. However, difficulties can arise with probability analyses if there is limited input data available. For example, it should not be assumed that input parameters always have a simple normal distribution about some mean value. In many instances the shape of the distribution function for the input parameters is unknown, and so even with probability analyses, engineering judgement is often used to assume the shape of this distribution function. Probability analyses can be a useful way of analysing slope stability problems, providing the assumptions on which they are based are fully recognised. A probability analysis facility is available within ***GALENA***.

2.6 Software Validation

The ***GALENA*** software system has undergone extensive validation at each stage of development, as well as now being "assessed" by a vast number of users world-wide, and invariably having its results compared with those of other slope stability analysis programs and spreadsheets. ***GALENA*** has also been used for benchmark testing (ACADS 1989) with other software packages and the results have been very favourable (full details are available on request). Some sample model files, which were actually used in the benchmark testing, are provided with ***GALENA*** to assist with software familiarisation and model definition.

As a means of verifying the limit equilibrium method of analysis, a slope configuration previously evaluated by ***GALENA*** using the Bishop Simplified method was modelled using the FLAC program marketed by ITASCA Corp.

The original ***GALENA*** analysis (using Version 1 of ***GALENA***) investigated the stability of a 20m high, 70° clay slope. The clay was assigned the following soil parameters:

c = 42 kPa phi = 20° Unit Weight = 18 kN/m^3

The result image from this ***GALENA*** analysis is shown in Figure 2.1 following. The Factor of Safety is virtually at 1 (actual value is 1.054), and such a slope is thus on the brink of failure.

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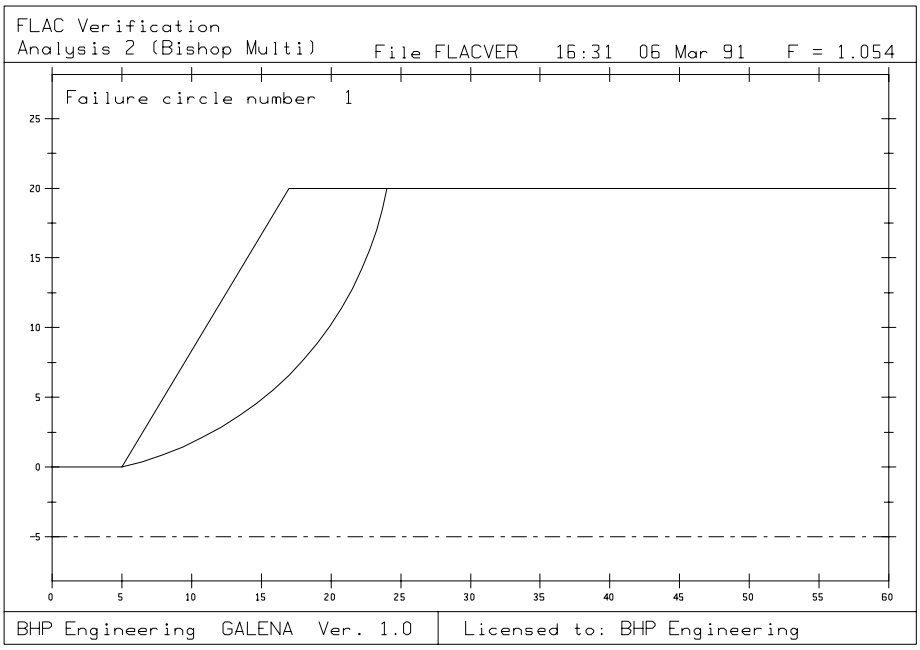

Figure 2.1

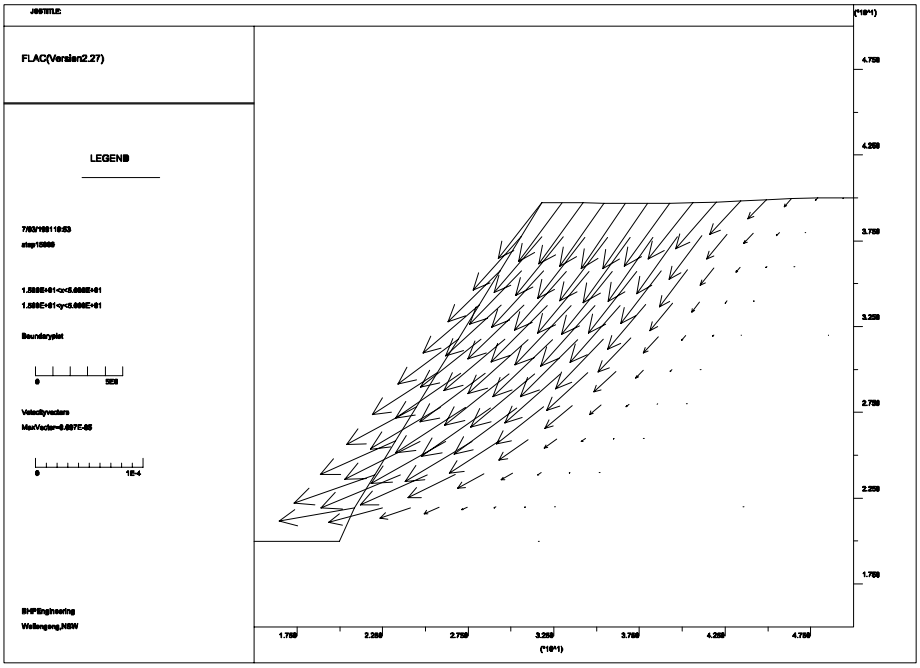

Figure 2.2

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The FLAC model was constructed using the same density and friction angle, while elastic properties were assigned that were consistent with a soil of this nature. Initially a higher cohesion, 60 kPa, was used; this was steadily reduced until continuing displacement was observed.

The cohesion was then reduced to 42 kPa and the graphic output is shown in Figure 2.2. It can be seen that some of the material has started to move, and the moving mass is broadly delineated from the relatively undisturbed soil by an arcuate surface.

Two particular points arise from this comparison between the limiting equilibrium ***GALENA*** analysis and the Continuous Element method of FLAC:

(i) The two approaches yield the same basic conclusion, i.e. the slope configuration is unstable. FLAC does not yield a Factor of Safety as such; the various parameters have to be varied until a condition of incipient failure is found. A limiting equilibrium program like ***GALENA*** can achieve this much more rapidly.

(ii) The failure surfaces defined by the two methods are in only approximate agreement. This is because the actual position of the yield surface will depend on elastic as well as shear strength properties. Thus extremely refined searching for minimum Factor of Safety slip circles with any limiting equilibrium method of analysis has no real value.

For most design and backanalysis purposes, ***GALENA*** will obtain valid, useable answers to the problem much more quickly than more complex methods. Even where the circumstances of the problem demand the application of Continuous Element or Finite Element methods, ***GALENA*** can be used to define the limits of the problem and thus save a lot of modelling time.

2.7 System of Units

GALENA will operate with any internally consistent system of units. The recommended units for the S.I. and USA systems are outlined below:

Parameter and Applications		S.I.	USA
Length	All surfaces and profiles	Metres (m)	Feet (ft)
Force	External forces	kN	lbf
Unit Weight	Material properties Water / medium-above-ground	kN/m^3	lbf/ft^3
Stress	Material properties (cohesion, UCS) Distributed loads	kN/m^2 (kPa)	lbf/ft^2
Seismic	Earthquake loads	Dimensionless (calculated as a fraction of total weight of sliding mass)	

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Pore pressure	R_u	Dimensionless (calculated as fraction of slice weight)

Notes: 1) ***GALENA*** requires unit weights to be used, ***not Densities***, as the program uses this directly in calculating the various slice forces.

2) Distributed loads are input as ***Stresses.***

Selected Conversion Factors

1 ft	=	0.3048 m	1 lbf	=	0.00445 kN
1 m	=	3.28 ft	1 kN	=	224.82 lbf
1 lbf/ft^2	=	0.04788 kPa	1 lbf/ft^3	=	0.1571 kN/m^3
1 kPa	=	20.885 lbf/ft^2	1 kN/m^3	=	6.366 lbf/ft^3

Typical Conversion Examples

	S.I.	USA
Cohesion	75 kPa	1566 lbf/ft^2
Friction Angle	28°	28°
Unit Weight		
(Clay)	19 kN/m^3	121 lbf/ft^3
(Fresh water)	9.807 kN/m^3	62.43 lbf/ft^3
External force	50 kN	11,241 lbf
Distributed Loads	100 kPa	2088 lbf/ft^2
Pore Pressure (R_u)	0.25	0.25
Earthquake load	0.15	0.15

2.8 Modelling Capability

As part of an optimisation process for ***GALENA***, limits are placed on certain parameters. These limits are under constant review and are currently set as follows:

Model Parameter	Maximums or Limits	
Project Title	1	(110 characters per title)
Analysis Title	1	(per analysis; 80 characters per title)
Slope Surface	1	(50 points per surface)
Material Profiles	40	(50 points per profile)

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Material Properties	30	(40 descriptor characters per material)
Phreatic Surface	1	(50 points per surface)
Piezometric Surfaces	24	(50 points per surface)
Distributed Loads	20	
Earthquake Loads	1	
External Forces	30	
Failure Surface	1	(50 points per surface)
Annotation (Text)	50	(80 characters per annotation)
Pointers	30	(3 styles)
Analyses	-	(unlimited)
Multiple Analysis Trial Surfaces	-	(unlimited)
Sarma Slice Boundaries	20	
BackAnalysis Curves	10	(per analysis)
Probability Analysis Materials	3	(per analysis)
Probability Simulations (analyses)	25000	(per analysis)
Grid Accuracy	-	(definable)

2.9 Conventions Used

Throughout this Users' Guide key presses (other than for data entry) are indicated with arrow brackets thus < >, e.g. <Enter> is for the Enter key; <P> is for the 'P' key. Shortcut/accelerator keys or key combinations are similarly shown, e.g. <Ctrl+Pg Dn> is for the Ctrl key held down and the Pg Dn (Page Down) key pressed.

Italic and bold fonts are used to highlight important information – in most cases such information (and additional explanation) is placed in a separate paragraph headed '***Note:***' – with the information then following.

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2.10 On-line Help

ToolTips are provided for all toolbar buttons - to use simply move the mouse cursor to a point over any one of the toolbar buttons – a small text box (ToolTip) will appear after a second or two describing the toolbar button function.

On-line Help is available for most dialogs and for all options and model definitions. On-line Help is accessed by pressing the F1 key; if a dialog is open at the time the F1 key is pressed then specific help for that dialog will appear, otherwise the Help Contents or Index will appear.

This Users' Guide is available from within ***GALENA*** at most times, and accessed either from the main menu, a toolbar button, the F2 key or from drop-down menus accessed with the mouse right button. If you prefer a hardcopy of this Users' Guide simply print it to your own printer at a size of your choice.

Also included on the main menu are options to connect to the ***GALENA*** website to learn of the latest with ***GALENA***, and for you to check on available updates and upgrades. Options are also included that make it easy for you to send your model file to a colleague, or to Clover Technology in the unlikely event that you are having problems with model definition.

2.11 References

ACADS, 1989, "Soil Slope Stability Programs Review"

ACADS Publication No U255, ACADS Australia

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GALENA can be started via the Windows Start menu through Programs→Galena→Galena 4.0, or via a shortcut Icon on the Windows Desktop. ***GALENA*** displays a banner and then the main window with structures and displays as further described within Section 3.1. Section 3.2 describes the mouse and keyboard controls available to manipulate the window, create and process models, and examine analysis results; Section 3.3 describes ***GALENA*** model files; and Section 3.4 (Quick Start to ***GALENA***) includes a short tutorial on ***GALENA***.

Descriptions of the various menu options are provided through the on-line Help function in ***GALENA.*** Information on stability analysis, in general and as related to ***GALENA,*** is included in Section 4 (Stability Analysis), and information on soil and rock strength estimation is provided in Section 5 (Soil & Rock Strength).

3.1 Main Window Structure and Display

The main ***GALENA*** window has the usual Windows-style menu system, which contains options for file control, data definition, edit functions, view control, process control and accessing of tools, results and help functions. Shortcut keys or key combinations, where available, are shown adjacent to the menu option on the drop-down menus.

A selection of toolbar buttons also appears in the upper and left/lower areas of the window and a status bar in the lower area of the window. Currently two toolbars are available – the Main Toolbar is displayed below the menu (upper window area) and the Data Definition Toolbar is displayed either to the left or at the bottom of the window (above the status bar) depending on the screen resolution available. ToolTips are displayed for each button as the mouse cursor is placed above each in turn. Both toolbars are displayed at start-up and the definition toolbar can be removed if required.

The main part of the window is the drawing pane - the area where models are displayed graphically and where the mouse-draw function is performed.

The status bar below the drawing pane has 6 segments with displays for the following:

(i) Current model file name - shown while a model file is open and named;

(ii) Analysis number and total analyses - changes as new analyses are added to a model; shown in the form 'An 1/3' (analysis 1 of a total of 3 in this example);

(iii) Analysis method for the current analysis, and vector distance and direction during mouse line draw in the form 26.2/17º (distance of 26.2 m/ft at 17 degrees above/below horizontal in this example);

(iv) Mouse cursor position within the drawing pane in the form 128.5/76.0 (x-position of 128.5 m/ft and y-position of 76.0 m/ft);

(v) Mouse line draw status – the letters MLD will be displayed while mouse line draw is active;

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(vi) Messages - general messages are displayed here as necessary.

3.2 Mouse and Keyboard Inputs

3.2.1 Mouse Input

The left mouse button is used to select menu items, toolbar buttons, dialog buttons and dialog fields for data entry, to select points during mouse line draw, to indicate positions during definition of distributed loads, external forces and circular failure surfaces, and to zoom in while zoom is active.

The right mouse button is used to access floating menus where available, to terminate mouse line draw, and to zoom out while zoom is active.

If your mouse has a wheel it can be used to scroll through values within dialog fields that have spinners (up & down arrows on the right side of the field).

If your mouse has a wheel or a middle button it can be used to open and close the Model Structure window displaying the model structure in a tree view. The wheel accesses this feature by being pressed down, as with mouse buttons.

3.2.2 Mouse Line Draw

Mouse line draw is the process used when drawing surfaces, profiles and slice boundaries, which are represented by single-segment or multi-segment lines. The left mouse button is used to indicate the beginning and ending of a line/segment. Line draw availability (for selected options) is indicated in the status bar and as described below.

When line draw is available the cursor will change shape to a crosshair when moved off the dialog area. The cursor can be moved to any point within the drawing pane and its position will be shown as an x/y co-ordinate in the status bar - moving the cursor will change the indicated x/y co-ordinate value. The displayed x/y co-ordinate value will be within the range set by the axis limits, and will show values according to the accuracy currently set – an accuracy of 1.0 will cause displayed values to be rounded to the nearest whole number (1.0) and displayed as 15/38 for example.

(i) Slope Surface, Material Profiles, Phreatic Surface, Piezometric Surfaces.

To draw a single-segment or multi-segment line:

- Move the mouse cursor to the desired x/y position;
- Click (press and release) the left mouse button - at this stage the current dialog will disappear to provide a refreshed model image within the drawing pane, and MLD (Mouse Line Draw) and the number of the last point defined and number of total available points will be displayed in the status bar;

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- Move the mouse - a line joining the last position with the current mouse crosshair position will be displayed
- Continue moving the mouse until the cursor and the end of the line are at the desired x/y position for the end of the line, or the end of the first segment of a multi-segment line;
- Click the left mouse button again - the line drawn thus far will refresh.

To complete a single-segment line:

- Click the right mouse button.

To continue with a multi-segment line:

- Move the mouse cursor to the desired x/y position;
- Click the left mouse button again;
- Repeat this move-click process until the desired multi-segment line has been defined - the last point number in the status bar display is updated during definition;
- When the desired line has been defined click the right mouse button.

The current dialog will be redisplayed with the x/y co-ordinates of the ends of the line, or those making up a multi-segment line, in a grid within the dialog.

(ii) Sarma Slice Boundaries

When drawing Sarma slice boundaries the procedure is as described in (i) above except that the right mouse button option as described is not available - once the two ends of the slice boundary are defined the Sarma Slice dialog will be redisplayed as only two x/y co-ordinates are required to define a slice boundary.

Once a mouse line draw operation is complete the returned x/y co-ordinates in the grid may be edited manually if required.

3.2.3 Mouse Area Definition

Options that require an area to be defined by lower left and upper right x/y co-ordinates, such as the Image Window option can be defined using the mouse and a rubber-banding technique. Availability of this technique using the mouse is indicated the status bar and as described below.

When mouse area definition is available the cursor will change shape to a crosshair when moved off the dialog area. The cursor can be moved to any point within the

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drawing pane and its position will be shown as an x/y co-ordinate in the status bar - moving the cursor will change the indicated x/y co-ordinate value. The displayed x/y co-ordinate value will be within the range set by the axis limits, and will show values according to the accuracy currently set – an accuracy of 0.5 will cause displayed values to be rounded to the nearest 0.5 and displayed as 17.5/36.5 for example.

To define an area:

- Move the mouse cursor to the desired lower left x/y position;
- Press and hold down the left mouse button - the current dialog will disappear to provide a clear and refreshed model image, and the mouse cursor will change shape to a south-west/north-east double-ended arrow;
- Move the mouse until the cursor is at the desired upper right x/y position - a rubber-band box will define the area and will stretch and shrink as the mouse is moved - once the desired area is defined release the mouse button.

The current dialog will be redisplayed with the minimum and maximum x/y co-ordinates for the defined area within the dialog. The returned x/y co-ordinates may be edited manually if required.

3.2.4 Keyboard Input

A number of dialogs are presented in the course of operation of ***GALENA***. Where dialogs with separate fields are presented the <Tab> key can be used to move between fields. When a dialog button is tabbed to the active button is shown with a dotted line inside its perimeter; pressing the <Enter> key will activate the option that button represents. Dialog buttons containing text with an underlined letter can be activated by holding down the <Alt> key and pressing the underlined letter key (e.g. <Alt+O> selects the OK button on most dialogs). Where dialogs containing grids are presented movement within the grid is by use of the keypad arrow keys.

To access the main menu press the <Alt> followed by the underlined letter key for the desired option. Various menu options have keyboard accelerators (shortcuts) and these are shown next to the menus options. A particularly useful accelerators key is the F4 key, which activates model processing (main menu option Process-All Analyses).

3.2.5 Numeric Input

When using ***GALENA***'s dialog system of data entry it is *not* necessary to type in the decimal point or trailing zero of real numbers (enter 20 for 20.0 for example). ***GALENA*** automatically reads and records real numbers where required.

It will be necessary to enter real numbers with the decimal point and trailing zero if data is entered in ***GALENA***'s Datasheet editor or during any other form of editing of ***GALENA*** Model Files.

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3.2.6 Grid Controls

Some of ***GALENA***'s data definition dialogs contain grids for co-ordinate value display and/or entry. Most options contain simple one or two column grids, and keyboard arrow keys provide convenient movement between grid cells.

Dialogs that contain grids also contain specific Insert Row and Delete Row buttons for use with individual rows, and their use is recommended in preference to complex cut/copy row manipulation (described below) for row insertion or deletion.

All of the grids used in ***GALENA***'s dialogs can be manipulated using the standard Windows cut, copy and paste options – individual cells, rows and columns, groups of cells, rows and columns and blocks of cells can all be manipulated in this way.

To select and copy a single cell double-click on that cell (the contents will be highlighted) and select <Ctrl+C>, or click the right mouse button, while the mouse cursor is over that cell, and select Copy from the floating menu presented. An individual cell can also be selected by clicking the cell once and then clicking the right mouse button, while the mouse cursor is over that cell, and then selecting Select All from the floating menu.

To select:

- Single rows of cells - click on the row label to the left of the cells.
- Single columns of cells - click on the column header above the cells.
- Multiple rows - click on the row label of the first row, hold down the <Shift> key and then click on the row label of the last row. *Only rows that are visible in the grid at the time of a cut or copy operation will be cut or copied – selected rows that move beyond the visible grid area as the result of a vertical scroll will not be included.*
- Multiple cells – double-click in the first cell, hold down the <Shift> key and then click in the last cell. *Only cells that are visible in the grid at the time of a cut or copy operation will be cut or copied – selected cells that move beyond the visible grid area as the result of a vertical scroll will not be included.*
- Multiple columns - click on the column header of the first column, hold down the <Shift> key and then click on the column header of the last column.
- All cells - click on the box that is above the row headers and to the left of the column headers.

Once any cell, row, group of cells or column is selected the right mouse button can be clicked while the mouse cursor is over the selection, to bring up a floating menu with options to Cut, Copy Paste and Delete those cells selected. The Undo option on the floating menu is available for individual cells where the contents have been deleted.

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Cell/row/column contents that are cut or copied can be then pasted into other cells/rows/columns on the same grid, other grids within ***GALENA*** or to spreadsheets (e.g. Excel, Lotus 1-2-3, etc.). The same is true for cells cut/copied from spreadsheets – they can be pasted directly into ***GALENA*** grids. The normal restrictions on matching areas apply (e.g. three columns cannot be pasted into two columns, etc.).

The cut/copy/paste facility available for use with grids provides a quick and simple way to move the contents of grids into and out of ***GALENA***.

Note: *When cutting or deleting rows from grids with cut/delete options it is important that subsequent rows be moved up and that no empty rows are left within defined rows* ***– if model data is accepted with blank or empty rows within rows containing data only those grid rows up to the blank row will be retained for use.***

3.3 Galena Model Files

GALENA operates by analysing a model that is created to represent a slope or excavation. A model can be defined as the data components necessary for an analysis to be undertaken. The basic data components **that must be defined for an analysis** include at least one material profile, physical properties at least one material that can be associated with that profile, a slope surface, a failure surface, and a method of analysis. These component parts that make up the model are stored in a model file, which is loaded for (further) definition and processing. ***GALENA*** includes facilities for the creation and processing of models, and examining the results of processing using methods described in this Users' Guide.

When processing is initiated, model files are read in a streamed manner and the various parameters set as they are encountered in the model file. Similarly, analysis statements initiate methods of analysis such as a Bishop analysis or Bishop backanalysis using the parameters that have been *set to that point*. By utilising model files in this way ***GALENA*** provides a powerful system where a model can be created with certain parameters, an analysis undertaken, one or more parameters can then be modified and another analysis undertaken to quickly ascertain the effects of such parameter changes, all within the one processing stream. It is not necessary to re-define all parameters for the subsequent analysis in such cases, only the parameters to be modified.

Neither is it necessary to re-define parameters before running another analysis. A Bishop analysis can be run on a model with defined parameters, then a Spencer-Wright analysis can be run on the same model with the same parameters, all within the same model. In this way direct comparisons can be made between the results of each method, if desired. These two basic procedures allow other parameter and analysis combinations that go towards making ***GALENA*** so powerful in its application.

GALENA assigns an Analysis number, incrementally, to each analysis defined during model creation, or encountered during model processing. During model creation

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GALENA assigns *Analysis 1* up to and including definition of an analysis method (including a method for backanalysis or probability analysis). Once an analysis method has been defined ***GALENA*** assigns *Analysis 2* up to and including the definition of the next analysis method. However, if no further analysis methods are encountered there will only be one analysis - *Analysis 1*. There is no limit to the number of analyses that can be defined in this way within a single model.

When a model is opened ***GALENA*** determines the total number of analyses defined for that model and displays the model with the parameters defined for the first analysis – Analysis 1. The analysis number appears within the title bar of all Define menu options and with the total number of analyses in the status bar, at the bottom of the window – these values change as analyses are added and as subsequent analyses within a single model are selected for display and/or definition.

Once a model has been opened its structure can be viewed as a tree view, similar to that used for the Windows Explorer 'Folder View'. The Model Structure window can be opened via a main menu View option, a toolbar button, and the floating menu available during model definition, and by clicking the mouse middle button or by pressing down on the mouse vertical scroll wheel. Each Analysis is shown with definitions specific to each analysis in an expanded view. The Model Structure tree is refreshed whenever a model is saved or reloaded.

3.4 Quick Start to Galena

This section is specifically designed for those users wishing to simply and quickly run a slope stability problem without reading the ***GALENA*** Users' Guide in detail. The model created here is very simple and not all of ***GALENA***'s definition capabilities are utilised.

Once ***GALENA*** has been installed and setup on a suitable PC it is ready for use. Creation of a model from scratch can be undertaken using either the menu system, or ***GALENA***'s toolbars for standard functions and data definition - both are described here.

Notes: *The symbol indicates mouse input, movement or selection; the symbol indicates keyboard input; the ⇒ symbol indicates the start of a new definition.*

Key presses are bracketed and indicated thus < >, e.g. <Enter> is for the Enter key; <P> is for the 'P' key.

Text or values to be entered are contained within quotes, e.g. 'Test' or '20.0' ***– do not include the quotes*** *when entering text or values.*

To verify a toolbar button move the mouse cursor over the toolbar button – a small text box (ToolTip) will appear after a second or two describing the toolbar button function.

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⇒ Double-click the ***GALENA*** shortcut on the Windows desktop, or select ***GALENA*** from the Start menu - Programs→Galena→Galena 4.0.
Or
Press the keyboard Windows button that accesses the Start menu, press <P> for Programs, arrow to Galena, press <Enter>, and arrow to Galena 4.0 and press <Enter>.

GALENA will start and display an opening banner while the program is loaded.

⇒ Click on the Model Title button on the Data Definition Toolbar.
Or
Press <Alt> for the menu, then <D> for Define, <T> for Titles, <M> for Model.

The Model Title dialog will appear. Enter 'Slope Stability Analysis Trial 1' (without the quotes), and click OK or press <Enter> to accept a title for this model.

⇒ Click on the Material and Water Properties button on the Data Definition Toolbar.
Or
Press <Alt> for the menu, then <D> for Define and <M> for Material & Water Properties.

The Material & Water Properties dialog will appear. Enter 'Clayey Gravel' (without the quotes) for the material in the Description field.

Click the Colour field button (marked '…' to the right of the Colour field).
Or
Press <Tab> to move to the Colour button and press <Enter> or the <Spacebar>.

The Colour dialog will appear. Use the mouse to select a colour or use the keyboard arrow keys to select a colour (a light colour is recommended, e.g. yellow), and select OK or press <Enter>. A colour band, in the selected colour, will be displayed below any Material Profile that is defined to have this material below it – any particular material can be used below more than one Material Profile.

Click on the Unit Weight field.
Or
Press <Tab> to move to the Unit Weight field.

Enter '20' (without the quotes) in the Unit Weight field to assign material unit weight.

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Click in the PWP from Phreatic or Piezometric Surface field to check this option.
Or

Press <Tab> twice to move to the PWP from Phreatic or Piezometric Surface field and press the <Spacebar> to check this option.

This indicates to ***GALENA*** that pore water pressures within this material should be calculated from phreatic or piezometric surfaces.

Click in the Mohr-Coulomb tab within the Strength Model group.
Or

Press <Tab> to move to the Mohr-Coulomb tab within the Strength Model group and press the <Spacebar> to select this option.

This selects the Mohr-Coulomb criterion using c & phi as strength parameters.

Click in the Cohesion field within the Strength Model group.
Or

Press <Tab> to move to the Cohesion field within the Strength Model group.

Enter '30' (without the quotes) in the Cohesion field to set C at 30 kPa (metric unit).

Click in the Phi field within the Strength Model group.
Or

Press <Tab> to move to the Phi field within the Strength Model group.

Enter '19.6' in the Phi field to set ϕ (friction angle) at 19.6°.

Click in the Water (in-ground) field within the Water/Medium Unit Weights group.
Or

Press <Tab> three times to move to the Water (in-ground) field within the Water/Medium Unit Weights group.

Enter '9.81' in the Water (in-ground) field.

Click in the Water/Medium (above-ground) field within the Water/Medium Unit Weights group.
Or

Press <Tab> to move to the Water/Medium (above-ground) field within the Water/Medium Unit Weights group.

Enter '9.81' in the Water/Medium (above-ground) field.

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Note: ***GALENA*** *does not default to a universal value for the unit weight of water, as it is a unitless system allowing you to use either SI or Imperial/US units.*

This completes definition of the Material and Water Properties (in metric units for this example). Click the OK button or press <Enter> to accept the entered values.

⇒ Click on the Axis Limits button on the Data Definition Toolbar;
Or
Press <Alt> for the main menu, then <D> for Define, then <X> for Axis Limits;

The Axis Limits dialog will appear. Enter '10' for X-axis minimum, '80' for X-axis maximum, '0' for Y-axis minimum, '40' for Y-axis maximum and click the OK button or press <Enter>. A grid with these limits is displayed.

⇒ Click on the Material Profiles button on the Data Definition Toolbar.
Or
Press <Alt> for the menu, then <D> for Define and <P> for Material Profiles.

The Material Profiles dialog will appear.

Move the mouse cursor crosshair to x/y co-ordinate 20/35 (the cursor x/y co-ordinate is displayed in the status bar), click (press and release) the left mouse button (the dialog will disappear), move the mouse to x/y co-ordinate 70/35, click the left mouse button again, and then click the right mouse button (the dialog will re-appear).
Or
Enter the following x/y co-ordinates into the dialog grid: '20' (X-Position), and '35' (Y-Position) in row 1 and '70' (X-Position) and '35' (Y-Position) in row 2 (use the arrow keys to move within the grid).

Note: *When using the dialog system of data entry it is not necessary to type in the decimal point or trailing zero for numbers such as 20.0 for example.*

From the 'Material beneath this Profile' drop-down list box select the first line shown (1 - Clayey Gravel). This drop-down box will list all material types defined using the Material & Water Properties option/dialog. As only one material type has been defined there will only be one within the selection. All material below this profile will have the properties of material 1 (Clayey Gravel). Click the OK button or press <Enter> to accept. The defined Material Profile is drawn as a dash-dot green line with a black dot at each end, with a colour band beneath of the colour selected with the Material and Water Properties option/dialog.

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Note: *When using the mouse line draw system the x/y co-ordinate values collected can be manually edited within the grid as required, once the dialog is re-displayed.*

⇒ Click on the Slope Surface button on the Data Definition Toolbar.
Or
Press <Alt> for the menu, then <D> for Define and <S> for Slope Surface.

The Slope Surface dialog will appear.

Move the mouse cursor crosshair to x/y co-ordinate 20/15 (the cursor x/y co-ordinate is displayed in the status bar), click (press and release) the left mouse button (the dialog will disappear), move the mouse to x/y co-ordinate 30/15, click the left mouse button again, move the mouse to x/y co-ordinate 50/30, click the left mouse button again, move the mouse to x/y co-ordinate 70/30, click the left mouse button again, and then click the right mouse button (the dialog will re-appear).
Or
Enter the following x/y co-ordinates into the dialog grid: '20' (X-Position), and '15' (Y-Position) in row 1, '30' (X-Position), and '15' (Y-Position) in row 2, '50' (X-Position), and '30' (Y-Position) in row 3, and '70' (X-Position) and '30' (Y-Position) in row 4.

This defines the surface of the slope being analysed and the x/y co-ordinates of points defining the surface. Edit the returned mouse-draw values if necessary, and click the OK button or press <Enter> to accept. The Slope Surface is drawn as a solid black line.

⇒ Click on the Phreatic Surface button on the Data Definition Toolbar.
Or
Press <Alt> for the menu, then <D> for Define and <h> for Phreatic Surface.

The Phreatic Surface dialog will appear.

Move the mouse cursor crosshair to x/y co-ordinate 20/15, click the left mouse button, move the mouse to x/y co-ordinate 70/15, and then click the right mouse button.
Or
Enter the following x/y co-ordinates into the dialog grid: '20' (X-Position), and '15' (Y-Position) in row 1, and '70' (X-Position), and '15' (Y-Position) in row 2.

Click the OK button or press <Enter> to accept. The Phreatic Surface is shown as a dashed blue line with a narrow blue colour band beneath.

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As the PWP from Phreatic or Piezometric Surface field was checked in Material and Water Properties ***GALENA*** will use the Phreatic Surface to calculate the pore-water pressures on the base of slices.

⇒ Click on the Circular Failure Surface button on the Data Definition Toolbar.
Or
Press <Alt> for the menu, then <D> for Define, <F> for Failure Surface and <C> for Circular.

The Circular Failure Surface dialog will appear. Ensure the Position Descriptors selected is "XL XR R" (default) - if not use the mouse and the drop arrow on the list box, or the keyboard arrow keys to select from the available descriptors.

The expanded (position) descriptors chosen are shown above the position fields.

Click on the X-Left position field.
Or
Press <Tab> to move to the X-Left position field.

The mouse cursor will have changed shape to that of a vertical bar with a right-pointing arrow on the left side.

Move the mouse cursor vertical bar to x co-ordinate 30/16, and then click the left mouse button (the x position is returned to the X-Left position field), or use the mouse wheel to scroll the values in the X-Left position field, or click on the up spinner (the arrow on the right side of the position field) until 30.0 is reached – the values will begin at 20.0 (the left extremity of the slope surface).
Or
Enter '30' in the X-Left position field, or use the up arrow key to scroll the values in the X-Left position field until 30.0 is reached – the values will begin at 20.0 (the left extremity of the slope surface).

Click on the X-Right position field.
Or
Press <Tab> to move to the X-Right position field.

The mouse cursor will have changed shape to that of a vertical bar with a left-pointing arrow on the right side.

Move the mouse cursor vertical bar to x co-ordinate 55/31, and then click the left mouse button (the x position is returned to the X-Right position field), or use the mouse wheel to scroll the values in the X-Right position field, or click on the up

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spinner (the arrow on the right side of the position field) until 55.0 is reached – the values will begin at 20.0 (the left extremity of the slope surface).
Or

Enter '55' in the X-Right position field, or use the up arrow key to scroll the values in the X-Right position field until 55.0 is reached – the values will begin at 20.0 (the left extremity of the slope surface).

Note: *When using mouse positioning to select the X-Left and X-Right positions it is not necessary to select a y co-ordinate that is coincident with the slope surface. The x co-ordinate need only be at the desired x-position (e.g. in the above example the x/y co-ordinate position for the X-Left position could have been 30/14 or 30/17.).*

Click on the Radius position field.
Or

Press <Tab> to move to the Radius position field.

The mouse cursor will have returned to an arrow shape.

Use the mouse wheel to scroll the values in the Radius position field, or click on the up spinner (the arrow on the right side of the position field) until 20.0 is reached – the values will begin at 1.0.
Or

Enter '20' in the Radius position field, or use the up arrow key to scroll the values in the Radius position field until 20.0 is reached – the values will begin at 1.0.

If the mouse wheel is used, or if the field spinner is used (either with the mouse or keyboard up arrow key) a circular failure surface will be drawn on the model image once a viable surface is available, and will be refreshed with each change to any of the position fields made with the mouse wheel or with field spinners. If values are entered from the keyboard the Refresh button can be used to refresh the image display once values have been entered for all three fields.

Note: *The Parameter Descriptors X-Left and X-Right refer to the x co-ordinates of the left and right intercepts of the Failure Surface* ***with*** *the Slope Surface. This method is recommended due to its simplicity of application.*

Click the OK button or press <Enter> to accept. The Failure Surface is shown as a solid red arcuate line.

⇒ Click on the Analysis Method button on the Data Definition Toolbar.
Or

Press <Alt> for the menu, then <D> for Define and <n> for Analysis Method.

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The Analysis Method dialog will appear. Ensure the 'Bishop Single' method is selected (default) - if not use the mouse or the keyboard arrow keys to select from the available methods.

This selects the Bishop Simplified method of analysis, which is suitable for the Circular Failure Surface defined. Click the OK button or press <Enter> to accept.

That completes the data definition for this model, and your model should look like that shown in Figure 3.1 below.

Figure 3. 1

The model must now be saved before processing can proceed.

⇒ Click on the Model Definition Complete button on the Main Toolbar.
Or
Press <Alt> for the menu, then <E> for Edit and <e> for Model Definition Complete.

The Save Model File As dialog will appear. Enter the name Example01 in the File name field (a .gmf extension is added automatically) and click the Save button or press <Enter>.

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The model definitions will be saved to disk, reloaded and the newly created model displayed on-screen (the model file and data will be checked during reloading and any errors will be reported). The Model Title is shown in the main window title bar and model file name in the status bar.

The completed model is now ready to be processed using the parameters defined.

⇒ Click on the Process All Analyses button on the Main Toolbar.
Or

Press <Alt> for the menu, then <P> for Process and <A> for All Analyses, or press the <F4> key.

GALENA will clear the main screen area, process the model data, graphically display the model in an Analysis Result window, display any errors in a Model Processing – Errors and Warnings window, and include the Factor of Safety within a dialog that includes analysis information. The resultant Factor of Safety should be 1.46 for this model, and the ***GALENA*** window should look like that shown in Figure 3.2 below.

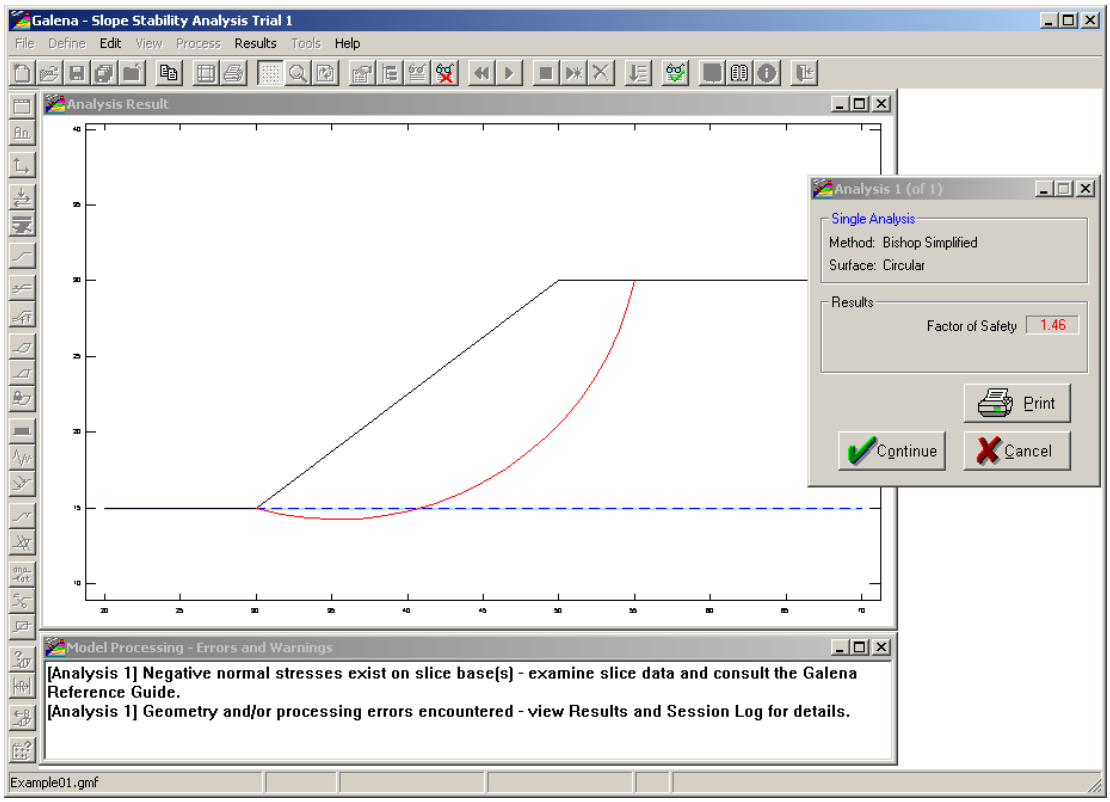

Figure 3. 2

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Once the analysis results are presented graphically and within the results dialog a number of options become available, namely:

- Continue – proceed to processing of any subsequent analyses, or complete the processing stream and reload the model if there are no subsequent analyses;
- Cancel – exits the processing stream and reload the model;
- Print – displays the Print dialog, which provides for printing of:
  - Analysis result images;
  - Detailed analysis results (model data, analysis results, slice information);
  - Session log (details of the current ***GALENA*** session, including errors).
- Menu options, including:
  - Edit-Image Display-Show Vertical Slice Boundaries – include or exclude slice boundaries (on the result image);
  - Edit-Figure Number – define a figure number for hardcopy analysis result images;
  - Edit-Copy – copy the result image to the Windows clipboard for pasting into a word processor document;
  - View-Session Log – details of the current ***GALENA*** session, including errors;
  - Results-Current Analysis Results – detailed analysis results (model data, analysis results, slice information)
  - Help-On-line Users' Guide – this Users' Guide document.

The menu options described are also available from a floating menu that can be accessed by clicking the right mouse button while the mouse cursor is over the result image window.

To complete processing of this model:

⇒ Click on the Continue button on the Results dialog.
Or
Press <Tab> until the Continue button is highlighted and press <Enter>.

The Analysis Results window and results dialog are cleared, and the model is reloaded and displayed on-screen.

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It is possible to now experiment with different slope surfaces, material properties, water table (phreatic surface) positions, etc. simply by redefining parameters and processing the model, but it is firstly recommended that Section 4 (Stability Analysis) be studied for a better understanding of issues that may affect results from, or influence analysis of, your models.

GALENA includes a number of example model files to demonstrate the principles and features described briefly here. These examples would have been copied to an Example directory (as a sub-directory of the ***GALENA*** program directory) during Installation, and may be copied, edited and modified to gain experience.

The model described is available with ***GALENA*** and would have been copied to the Examples directory during installation.

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As you become more familiar with ***GALENA*** and undertake more sophisticated analyses with more complex models, certain extreme conditions may be encountered which may be beyond ***GALENA***'s normal analytical scope.

This Section is intended to clarify and assist with models and analyses by providing additional guidance on definition, applicability, analysis techniques and result interpretation, as well as highlighting difficulties that may be encountered and their possible resolution.

4.1 Material Profile Definition

Material profiles in ***GALENA*** are defined as a line or series of lines, in turn made up of a series of x/y co-ordinate pairs, to represent the upper limit of a material layer - at least one material profile must be defined for a model.

We recommend that material profiles be defined according to original geology, or in as simple a manner as possible. For example, the easiest way to define the top material profile is as a horizontal line above the expected slope surface level. This can be achieved by simply defining a line of two points, one at or near the x-axis minimum and one at or near the x-axis maximum, or at the horizontal limits of the slope surface to be defined. We further recommend that profiles be defined in a 'top-down' approach - i.e. the topmost profile be defined first, then the next profile below that, and so on. This start-at-the-surface approach approximates that used when mapping drilled holes, pits and trenches, and generally avoids definition of unnecessarily complex profiles.

When modelling a simple horizontally layered slope it is usually easiest, and quickest, to define the material layers as a series of horizontal lines that extend from and to the axis or model limits, rather than to have a number of material profiles that follow the slope profile before branching off at appropriate levels on the slope surface. The slope surface is used to define the surface of the slope and when material profiles are defined as described ***GALENA*** simply and efficiently handles what has been a problem for many in the past, who ask 'what do I do if I want to move the slope surface - do I need to move all of the material profiles as well?'

When using material profiles to model enclosed bodies definition of profile co-ordinates should proceed clockwise around any such body and end with the last co-ordinate position being at the same position as the first - a closed polygon. Closed bodies, such as lenses and backfilled excavations can be modelled in this way.

In cases where one material boundary intercepts another, for example unconformities or beds that wedge out, care should be taken to ensure that the common point is defined for both material profiles.

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***Note**: A material profile can have several y co-ordinates for any x co-ordinate (i.e. they can be over-folded), provided none of the profiles cross - material profiles should be split and defined separately in cases where crossing is expected or required.*

For complex geology, material profiles need to be defined with caution. For steeply dipping geology, a horizontal line should be used above the slope surface to ensure that all of the material to be defined is actually defined. Only material under the slope surface will be considered in analyses.

4.1.1 Reducing Excessive Profile Numbers

GALENA currently allows up to 40 material profiles, and for most geological models this is expected to be more than sufficient; typically eight or nine profiles are used.

An exception may be where features like stone columns, dykes or sheared zones cut through a layered system. If the sections of horizontal interface between the columns are treated as separate profiles the total number of surfaces could soon become unmanageable.

This can be avoided by entering the profile as a single surface which follows its natural line until it meets the column or dyke; from that point it coincides with the boundary of the column, running up over the top (or under the bottom) of the feature, resuming its proper alignment on the other side. The columns themselves can also be treated as a single profile by joining them at the bottom.

This increases the number of points on the particular profile, but as ***GALENA*** can currently handle 50 points per profile, this is not often a problem. A large number of profiles can coincide in this way without affecting the accuracy of the analysis.

Another option to reduce excessive profiles is to eliminate parts of the model that lie outside the possible range of failure surfaces - see Section 4.2 (Initial Failure Surface Selection) for further information.

A valid simplification of a model not only reduces profile numbers, but also is a sound engineering geological exercise that assists in comprehension of the problem. For example, two or three consecutive sand layers which only differ by a degree or two in friction angle can obviously be combined, especially if they are underlain by soft clay that will clearly dominate failure behaviour.

4.2 Slope Surface Definition

When using ***GALENA*** it is recommended that material profiles are defined to represent geology, as it would be before any slope was defined, excavated or created, and where possible or practical, before slope surface definition. A slope surface is then defined, which in effect "cuts through" the defined profiles. If analysis reveals that the slope

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surface chosen is unsuitable and needs to be re-positioned the process within ***GALENA*** is straightforward – re-define the slope surface.

If material profiles are defined according to geology and not to match or follow the slope surface then there is no need to re-define any of the profiles. Additionally, there is no need to have common material profile and slope surface co-ordinates; therefore the slope can be re-defined to "cut through" the profiles at almost any position for almost any design.

While ***GALENA*** can handle a large number of co-ordinate points, permitting quite complex topographic surfaces, certain configurations may cause misleading results. It is assumed that in most cases the slopes being analysed are excavations, cuttings, embankments, or natural slopes with slopes less than vertical.

GALENA does not recognise overhanging slopes in calculations. When calculating the weight of the slices below the overhang, the overhanging material is ignored. Such cases should be modelled as vertical or near-vertical faces, provided no overhang is created. If a very large overhang needs to be modelled, consideration of moments and elastic behaviour put such a problem outside the scope of a limiting equilibrium analysis of this type - this also applies to tunnels, caverns or other underground spaces. Overhanging tension cracks are discussed in Section 4.2.1 below.

Note: ***GALENA*** *will work with both right-hand rising and left-hand rising slopes, but some caution should be exercised when using left-hand rising slopes. Bi-directional slopes such as dams or box cuts can be analysed within one model, but care should be taken when doing so (a bi-directional model file is included with the examples installed during installation of* ***GALENA****). For complex models, bi-directional slopes are probably best analysed as two separate cases. It is recommended that slopes be input rising to the right (right-hand rising) wherever possible.*

4.2.1 Including an Inclined Tension Crack

In the case of an inclined tension crack, any material **above** the tension crack is ignored in calculations; this is a valid assumption if the tension crack is inclined in the **opposite** direction to that of the slope, since the material above the crack would be left behind as an overhang after failure.

In the less likely case, that of a tension crack inclined in the **same** general direction as the slope, there is some error involved in ignoring the mass above the crack, since this mass would in reality contribute to the disturbing forces, so the true Factor of Safety would be lower than that reported by ***GALENA***. In practice, such cases would be very rare, but can still be modelled by replacing the tension crack with a local zone of material with the same density as the surrounding material, but with very low strength, and then constraining the failure surface to pass through this zone.

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4.3 Initial Failure Surface Selection

The amount of searching that is required when using the restraints and multiple analysis definitions can obviously be reduced if the initially defined surface is close to where the critical surface is likely to be.

In the case of circular type failures, a number of empirical criteria for the position of the circle centre and its radius can be found in the literature, e.g. Hoek and Bray (1981). In addition, the following guidelines may be useful:

(i) Generally for homogeneous slopes, the critical failure circle will pass through the toe of the slope, unless the break of slope is relatively gradual. Continuum modelling confirms this - see Section 2.6 (Software Validation).

(ii) In general, materials with relatively high cohesion and low friction angles will fail with smaller radius circles, with the head scarp closer to the crest, than in materials with higher phi (ϕ) values. (The extreme case is a pure ϕ soil, which in a dry or fully submerged case will fail on a plane dipping at the ϕ angle.)

(iii) Certain layers or bodies will resist failure due to their strength, and failure surfaces should be chosen to avoid such formations.

In the case of non-circular failures, the failure surface position may be determined by the geological structure. If, however, it is suspected that an unknown non-circular surface may have a lower Factor of Safety than a critical circle already calculated, this circle could be multiple-analysed as a non-circular surface using the SPENCER-WRIGHT method.

Whenever a multiple analysis of any kind is undertaken, the parameters of the critical surface should be checked to ensure that it does not lie at the limits of any of the restraints; if it does, further multiple analyses centred on that surface will be necessary.

4.4 Selection of Analysis Method

The BISHOP SIMPLIFIED method allows for the analysis of circular failure surfaces only, and as such is best suited for materials that are comparatively homogeneous and isotropic on the scale of the slope.

This obviously applies to soil materials, but the method is also applicable to highly jointed rock masses where there are no obvious potential planar or wedge failures.

As this method is the fastest running of those available in ***GALENA***, it is often convenient to run a BISHOP SIMPLIFIED analysis as a "first pass" check, even in cases where it is suspected that one of the other methods may actually be more appropriate. Also, it is not unheard of for a study and analysis of a day-lighting planar surface to indicate a satisfactory Factor of Safety, while a circular surface completely bypassing or cutting through that plane to be potentially unstable.

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The SPENCER-WRIGHT method can be used for both circular and non-circular failure surfaces in soil and rock slopes. Failure surfaces can be planar or curved, or be a combination of both of these shapes.

Both the SPENCER-WRIGHT method and the BISHOP SIMPLIFIED method will give almost identical results for circular failure surfaces, and so in most cases the BISHOP SIMPLIFIED method is preferred for simple circular failure surfaces. The SPENCER-WRIGHT method can have some mathematical convergence problems for very high or very low Factors of Safety. This will generally not present a problem since the exact Factor of Safety in these instances is usually not critical.

The SPENCER-WRIGHT method will generally operate well on failure surfaces that are concave. Where a failure surface is convex, or has a convex section along it, a warning message will appear, and the results should be thoroughly checked. A check using the SARMA method is recommended in this instance.

When using the SPENCER-WRIGHT method in ***GALENA*** a very powerful capability is available - **the ability to specify a circular failure surface initially and have the circular surface distorted to non-circular surfaces during a multiple analysis search for the minimum Factor of Safety.** The Help function provided in ***GALENA*** for Analysis Method has more information on this capability.

The SARMA method is used specifically for non-circular failure surfaces in soil and rock slopes and can be used to investigate other geotechnical problems such as foundations. Failure surfaces can be planar or curved, or be a combination of both.

The SARMA method of analysis is normally used for more complex stability problems where there is a requirement to have either a complex failure surface, non-vertical slices, to include faults, or where normal stresses on slice boundaries are likely to be critical. The SARMA method can be used both for slope stability problems as well as foundation problems provided a failure surface is specified.

Caution should be exercised when using the SARMA method, since a realistic solution may not be possible in all cases. For example, tensile stresses developed along a slice boundary indicate that failure would probably occur along that slice boundary and not along the failure surface. In this case the failure surface should be re-defined to a new position along that slice boundary, and the model re-analysed with the SARMA method.

It is often good practice to carry out a SPENCER-WRIGHT analysis on the same surface to assess the significance of non-vertical slice boundaries to stability.

4.5 Simulation Of Ground Anchors

Slope stability engineering often requires the use of artificial ground support (cables, rock bolts, shear pins, etc.) to prevent instability of some slopes and excavations. Many

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open-pit mining operations regularly use ground support to reduce overall excavation costs and therefore there is a requirement to optimise this ground support for maximum support efficiency.

However the simulation of the effects of a ground support system in a slope stability analysis program is not a trivial problem, and considerable additional research needs to be done in this area.

Some of the methods of simulating ground support and their problems are briefly described following:

(i) Point Force Method

This method of ground support simulation applies a point force (equivalent to the capacity of the bolt) to the surface of the slope. Initially, this method appears simple and correct. However, point forces applied near the crest of the slope would tend to de-stabilise the slope because of moment equilibrium considerations. Also the forces are applied to the surface of the slope ***not*** to the failure surface. *This is obviously not correct for most slope problems.*

(ii) Distributed Force Cones

An extension of the point force method is to distribute the force applied at the slope surface to the failure surface by assuming that a "force cone" can be drawn from the point of application of the "bolt" to the failure surface. In this case the area of influence of the cone increases very rapidly as the depth of the failure surface increases, and hence the stabilising stress applied also reduces very rapidly. In most rocks the area of influence of a rock bolt or anchor is probably much smaller than these imaginary "force cones". The length of embedment and position of attachment of a bolt or anchor is obviously also of great importance. Difficulties also arise when only part of the force cone intersects the failure surface.

(iii) Increase Failure Surface Cohesion

This method calculates the total force required to stabilise the slope and then applies this total force by using many cable anchors or rock bolts, each of a known force capacity. The number and spacing of anchors/bolts is then converted into a reinforcing stress. This reinforcing stress is then modelled in the stability analysis by increasing the cohesion on the failure surface by this amount. This is currently the commonest method used to simulate ground support for slopes and excavations.

Of the three methods described above, the last method is preferred, since it is simple and puts the onus on the geotechnical engineer to determine the appropriate increase in cohesion to be applied (easily calculated using ***GALENA***'s backanalysis capability) that would be equivalent to a ground support system.

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***Note**: You should be very careful when simulating the effects of ground support systems in slope stability analyses. In particular, the question should always be asked, "Can the full capacity of the ground support system be transferred to the failure mass?" In many weak rock masses the answer is NO, and some spectacular slope failures have occurred as a consequence of not considering this fact.*

Also, there are many factors that influence the capacity of the support system itself including grout, drilling, corrosion, angle of installation, etc.

The support system should be matched to the geology and the desired reinforcing effect, and it should be noted that artificial ground support might not be appropriate for some slopes.

4.6 Multiple Analysis Restraints

The restraints capability within ***GALENA*** is one of its most powerful features. Understanding how to efficiently use restraints can save time and effort, and lead more quickly to locating the potential failure surface with the minimum Factor of Safety.

4.6.1 Restraints and Critical Failure Surfaces

There are two basic approaches that can be applied to the use of restraints. The first involves setting restraints with wide ranges to each of the surface parameters – as wide as may be considered necessary – and then running one multiple analysis with the number of trial positions set as high as is practicable. This approach is best suited to small-scale slopes where the number of trial positions will provide sufficient coverage within the range defining the area of interest.

The second is probably more suited to large-scale slopes where it would generally be better to undertake an initial coarse search, followed by further searches using progressively narrower ranges. The following steps are presented as an example of this approach:

(i) Define the failure surface, set the restraints to cover the area of interest, and select a multiple analysis;

(ii) For the next analysis define the failure surface as 'critical' (***GALENA*** will use the surface (from the previous multiple analysis) with the lowest Factor of Safety), re-set the restraints to narrower ranges while the positions remain unchanged, and select a multiple analysis again;

(iii) Repeat step (ii) above, reducing the range again, and repeat (ii) again if necessary.

Use of both approaches is demonstrated in example model files provided with ***GALENA***, which would have been copied to an Example directory during installation, and may be copied and modified as required.

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4.6.2 Restraints and Circular Failure Surfaces

Restraints can allow failure surfaces to be generated that are geometrically or physically impossible for the slope being examined. For example, if X-Left or X-Right ranges are too broad some circles may intersect the slope surface such that very small circles result (e.g. at the crest or on the slope face). Broad restraints may even allow the generated failure circle to not intersect the slope at all. The defined ranges need to be appropriate to fit the size and geometric shape of the model.

Where restraint ranges result in failure surfaces that do not intersect the slope surface, or are above the slope surface, ***GALENA*** will abort the analysis of that particular surface. The omission will be recorded and processing will continue - the number of analyses aborted due to unacceptable geometry will be displayed within the Multiple Analysis Result Summary dialog, and within the analysis results.

Typical problems related to restraints that may be encountered during analyses are:

- Surfaces extending beyond the defined horizontal range, either of the slope or the material profiles;
- Surfaces passing above ground level. This is most commonly caused by benches and berms, toe drains, too short radii when XC, YC, R is defined, or too great a mid-point range in non-circular analyses;
- Convex angles or unrealistically tight angles in non-circular surfaces. ***GALENA*** will still attempt to analyse such surfaces, but will give an appropriate warning, and may fail to achieve a result.

The problems described above are also relevant to non-circular failure surfaces.

4.6.3 Restraints and Non-Circular Failure Surfaces

Much the same comments in Section 4.6.2 above can be applied to non-circular failure surfaces. The main difference is in the application of restraints to the general mid-point position of a failure surface. With circular surfaces the radius value controls the general mid-point position of a surface, however, with non-circular surfaces restraints are applied to X-Left, X-Right and Mid-Point positions only.

The mid-point restraint controls a *vertical range of variation* around the initially defined failure surface mid-point. Mid-point restraint ranges are generally more sensitive than radius restraint ranges. For example, a radius range of 25.0 on an initial radius of 125.0 will allow the radius to vary between 112.5 and 137.5 - this will still produce acceptable circles in most cases. A similar range applied to the mid-point on a non-circular surface could produce surfaces of wildly differing shapes, and quite possibly convex surfaces.

When using non-circular surfaces ***GALENA*** adjusts the positions of the other points on the surface to maintain the same general relative positions. If any of the generated surfaces has a convex point, ***GALENA*** will provide a warning - if excessive numbers of

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convex points are encountered it would be advisable to reduce the mid-point restraint range and re-process the model.

4.7 Use of Critical Acceleration – Sarma Analyses

The SARMA method calculates an "acceleration force" to determine the Factor of Safety and the method determines the relationship between this force and the Factor of Safety. In some instances this relationship is highly erratic, and it is recommended that this relationship be plotted to determine the admissibility of the analyses.

As a consequence of the iterative and convergent logic used by the SARMA method, the Factor of Safety alone is not a sufficient indicator of the stability; certain geometries will yield results that are highly misleading. For this reason, always check the critical acceleration, which should lie between zero and 1.0 for meaningful results.

When working with ***GALENA***, a reasonable maxim to bear in mind is that extreme and improbable models are likely to yield extreme and improbable results. **The best software does not eliminate the need for sound engineering geological reasoning.**

4.8 Numerical Errors - Limit Equilibrium Methods Of Analysis

For limit equilibrium analysis procedures, numerical errors are known to be associated with the following cases:

(a) Cohesive soil slopes with a shallow failure surface or where a high cohesive layer exists along the upper portion of the failure surface. Negative stresses may be generated towards the top of the failure surface.

(b) Where a steeply dipping section of a circular surface is present in the toe region, particularly when a relatively thin cohesionless layer overlies a thicker layer of weak clay. Similar problems may be encountered with non-circular failure surfaces where a sub-horizontal surface is present at shallow depth and connected to the ground (slope) surface by a steeply inclined section. Very large or negative stresses may result under these conditions.

(c) The application of a horizontal seismic coefficient for pseudo-static analyses using the BISHOP SIMPLIFIED method.

4.8.1 Negative Stresses towards the Top of a Slope

In cohesive soil slopes negative normal forces on the base of a slice may be computed, with the line of thrust or location of the side forces falling outside the boundaries of the slope and shear surface. These factors indicate that zones of tensile stress exist (Spencer 1968, Wright 1975). Numerical instability results when relatively high tensile stresses are encountered by the SPENCER-WRIGHT method.

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The position of the line of thrust is indicated by the L/H value (in analysis results) for the total stress case, and the L'/H for effective stress cases, where a phreatic surface is present. For negative L/H or L'/H values the line of thrust lies beneath the failure surface. Where the L/H or L'/H values exceed 1.0 the line of thrust lies above the slope surface. Ideally for effective stress problems, the L'/H value should lie within the middle third of the slice. Where tensile stresses occur near the top of a failure surface they may be eliminated by introducing a vertical tension crack at the top of the slope with the failure surface terminating at the bottom of the tension crack (Spencer 1968, 1973, Wright 1985).

The depth of the tension crack Z_o can be estimated from Rankine active earth pressure theory as follows (Wright 1985):

$$Z_o = \frac{2\,c_m}{\gamma \tan\left(45 - \frac{\phi_m}{2}\right)}$$

where: c_m is the mobilised cohesion being equal to c / Factor of Safety.
γ is the unit weight.
ϕ_m is the mobilised friction being equal to ϕ / Factor of Safety.

If the Factor of Safety cannot be estimated prior to the analysis a value of 1.0 should be employed.

For multiple analyses using the SPENCER-WRIGHT method, ***GALENA*** enables the tension cracks to be automatically generated by using the Tension Crack option and specifying an estimated depth for the tension crack. A tension crack depth greater than that indicated by the above equation should be avoided because of the potential for eliminating zones of compressive stress and over-estimating the Factor of Safety (Wright 1985). Values for the tension crack depth will generally be less than 2.0m (6½ft) with a further reduction recommended for slopes of limited height.

4.8.2 Very Large or Negative Stresses in the Toe Region

The problems associated with steeply inclined circular failure surfaces in the toe region of a slope were assessed by Whitman & Bailey (1967) with regard to the BISHOP SIMPLIFIED method, and a test factor m_a was identified as follows:

$$m_\alpha = \cos\alpha \left(1 + \frac{\tan\alpha \tan\phi'}{F}\right)$$

where: α is the inclination of the base of a slice.
ϕ' is the mobilised friction angle.
F is the Factor of Safety.

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This Test Factor is incorporated into the analysis results with values of less than 0.2 being unacceptable (Whitman & Bailey 1967).

Similar problems have been found to occur with the more rigorous analysis methods of SPENCER-WRIGHT and SARMA, and also with non-circular failure surfaces where a sub-horizontal section is connected to the ground surface by a steeply inclined plane. SARMA (1987) outlined a test factor Fm for the SARMA method and concluded that where the test factor for any slice is greater than or equal to unity, the failure surface should be rejected. The test factor F_m is calculated as follows:

$$F_m = -\tan\alpha \tan\phi'$$

The very large or negative stresses introduced by a steeply inclined failure surface through a cohesionless soil may be overcome by modifying the inclination of the failure surface in line with Coulomb passive earth pressure theory (Ching & Fredlund 1983, Wright 1985). The inclination then becomes a function of the side force inclination β and mobilised friction angle ϕ'_m (Wright 1985). The side force inclination for the SPENCER-WRIGHT method is contained within the analysis results and may be utilised for estimating the required failure surface inclination.

4.8.3 Application of Pseudo-Static Earthquake Coefficient

The BISHOP SIMPLIFIED method does not allow the seismic force *g* to be accounted for in force equilibrium equations in the vertical direction, which means that the effect of the seismic force on the normal force on the base of a slice is ignored (Wright 1985). The BISHOP SIMPLIFIED method may therefore produce incorrect results when a seismic force is applied and should be used with caution. The more rigorous SPENCER-WRIGHT and SARMA methods are recommended for use for pseudo-static analyses.

4.9 Quoting a Factor of Safety

Multiple analysis results and summary listings for the surfaces with the lowest stability show the Factor of Safety to three decimal places. This is to permit an evaluation of the rate of variation in Factor of Safety as different parameters defining the slip surface are varied, but as discussed in Section 2.1 (Commentary), Factors of Safety should never be quoted with such precision, since the parameters controlling slope stability can never be known that accurately.

The second decimal place is quite adequate, and for broad scale evaluations of general slope configurations and possible parameter ranges, one decimal place should suffice.

4.10 Interpretation of Slice Information

It is possible to obtain incorrect or unreasonable values for the Factor of Safety for some slope configurations and shear surface conditions when using limit equilibrium

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methods. These cases are usually associated with the generation of very high or negative stresses in some of the slices. ***GALENA*** displays warnings when negative stresses are present in one or more slices and the output file should be inspected before accepting the analysis result. The most commonly occurring problems encountered with the limit equilibrium methods of analysis are discussed further in Section 4.7.

4.11 BackAnalysis Results - Very High Friction Angles

In certain cases, for low values of cohesion, the necessary friction angle for a required Factor of Safety may exceed 45°. At this point, a backanalysis image curve will show that the indicated ϕ value rises a little and then actually decreases as c approaches zero. This is simply a mathematical "hiccup" resulting from the function used and the backanalysis curve should be regarded as unreliable in this range.

In reality, natural materials with true ϕ values of greater than 45° are very rare. Certain "locked" sands densified under glacial overburdens and interlocking rock masses at low confining pressures are the main cases and these can be modelled as c-ϕ materials. In any event, the main analytical part of ***GALENA*** will handle such low c high ϕ materials; the difficulty is in backanalysis only.

4.12 Run Failures

On rare instances a combination of model geometry and parameters may cause ***GALENA*** to 'crash' during an analysis. Although such combinations are normally captured and error messages reported you would generally find that such 'crashes' usually result from use of unrealistic model parameters. Should ***GALENA*** ever 'crash' model parameters should be carefully checked and adjusted as necessary.

If such 'crashes' persist after attempts to correct the problem as described please note any details provided and contact Clover Technology. Feedback from such instances usually assists and can sometimes provide the quickest and most efficient way to locate and correct such problems.

4.13 Inspect The Results

Finally, it should be emphasised that many problems can be the result of simple input errors - ***GALENA*** error messages, dialogs or the analysis results will most likely advise the 'what and where' of any problems. A common problem is non-definition of material properties for some part of the model and by examining the images it can usually be seen where this occurs. Inspecting the analysis results can quickly identify other problems such as high tensile forces or non-convergence.

Analyses can give results that are mathematically correct, but geotechnically illogical or trivial, such as tiny circles at slope corners or very flat circles almost coincident with the slope surface.

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Remember that an analysis investigation should never be finalised unless the analysis results have been inspected. The best program is not a substitute for engineering geological and geotechnical understanding.

4.14 References

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This section aims to provide guidelines, assistance and additional information when using ***GALENA***'s Soil and Rock Strengths option, which is accessed through the main menu Tools option, and with the selection of soil and rock strength parameters when defining or selecting material properties for ***GALENA*** models. Tables and references that are used with the Soil and Rock Strengths option are included within this section.

5.1 Soil and Rock Strengths

The Soil and Rock Strength option will initially display an 'About Soil Strength Parameters' dialog containing important information on selection of soil strength parameters. Once the Continue button on the 'About…' dialog is selected the Soil and Rock Strength Parameters dialog is displayed with two tabbed sub-dialogs - the first is for Soil Strength Parameters, and the second is for Rock Strength from RMR. To move between the two tabbed sub-dialogs either click on the appropriate tab or use the keyboard left/right arrow keys.

When the Rock Strength from RMR tab on the Soil and Rock Strength Parameters dialog is first selected an 'About Rock Mass Strength Determination' dialog is displayed containing important information on rock mass strength determination. Once the Continue button on the 'About…' dialog is selected the Rock Strength from RMR dialog is displayed. Neither of the 'About…' dialogs are displayed again during the current ***GALENA*** session.

Note: Only *within the Soil and Rock Strength options are Metric units (SI) assumed and output. See Section 2.7 (System of Units) of this Users' Guide for conversion factors to US units.*

5.1.1 Soil and Rock Mass Strength Estimation

Many factors influence the selection of strength parameters for design purposes and these are discussed by Lamb and Whitman (1969), Hoek and Bray (1981), Hunt (1986), Fell and Jeffery (1987). Laboratory testing is normally undertaken to determine the drained or effective shear strength parameters with peak, softened or residual values selected as appropriate. The selection of shear strength values must take into consideration the presence of discontinuities, with structure important for overconsolidated, fissured clays and rocks.

5.1.2 Using the Soil Strength Parameters Dialog

(a) Granular Soils

The Granular Soils group of the Soil Strength Parameters dialog displays a table of typical peak drained shear values for predominantly sandy soils (Unified Soil Classification - SM, SP, SW). Reference should be made to NAVFAC Design Manual DM-7 (or other similar reference) for values for predominantly silty or gravelly soils.

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Shear strength values should be selected in conjunction with the following comments:

- Grain shape influences ϕ with angular quartz grains increasing ϕ by 15% in the loose state and 30% in the dense state.
- At large strains, softened (ultimate) shear strength values are appropriate for dense sands, with peak ϕ values reduced by 10-25%.
- Although pure granular soils strictly have no cohesion, a small value is recommended for dense or "locked" soils to model steep Mohr envelopes at very low normal stresses.

The Granular Soils group of the Soil Strength Parameters dialog provides for input of an SPT "N" value for determination of a suggested drained ϕ (phi) value for sands, based upon a correlation with the SPT "N" value (Peck, Hanson and Thornburn 1953). This correlation is widely reported in the literature, however, significant scatter is expected about the correlation curve, and extreme caution is recommended when using this facility.

(b) Cohesive Soils

The Cohesive Soils group of the Soil Strength Parameters dialog displays a table of typical undrained shear strength values for clay soils. The C_u ($\phi = 0$) case for short-term conditions is usually only applicable to soft clays, with the use of Skempton's C_u - PI relationship recommended, where cohesion for normally consolidated clays is calculated for undrained conditions (i.e. $\phi = 0$) as:

$$C = C_i + (0.11 + 0.0037 \times PI) \times \text{effective overburden pressure}$$

where: C_i is the absolute value of the Cohesion value;
PI is the Plasticity Index.

Correlations of SPT "N" values with unconfined compressive strength are available in NAVFAC Design Manual DM-7 (1971) or other similar references.

Effective strength parameters for cohesive soils should preferably be determined by laboratory testing using the appropriate range of in-situ effective stress. The following guidelines may be adopted for preliminary design purposes:

(i) For normally consolidated soils c' = 0 with ϕ' calculated from the Soil Strength Parameters dialog using a correlation with the Plasticity Index (Terzaghi and Peck 1967).

(ii) The softened strength (ϕ'_s) and zero cohesion residual strength (ϕ'_r) are generally recognised as the upper and lower boundaries for slope failures in overconsolidated, fissured clays.

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(iii) Zero cohesion residual strength (ϕ'_r) should be used for pre-existing failure surfaces.

The Cohesive Soils group also provides for input of a PI (Plasticity Index) value for calculation of a suggested effective ϕ (phi) value for normally consolidated soils. Enter a PI value or use the spinner controls on the input field to select a value and then select the Calc button. A suggested effective ϕ (phi) value is displayed.

Correlations of ϕ'_r with soil index properties are widely reported, e.g. Skempton (1985), Mesri and Capeda-Diaz (1986), Lupini et al (1981), Kanji (1974). Typical values are as follows:

Material	ϕ'_r ° (deg)
Clay, sand and silt mixtures	12 - 24
Normally consolidated clay	4 - 14
Fissured clays and clay shales	9 - 12

Additional data for Compacted Soils is contained in Table 5.1 (Approximate Material Properties for Compacted Soils (NAVFAC, 1982)) following.

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Table 5.1 Approximate Material Properties for Compacted Soils (NAVFAC, 1982)

Soil Description	Class	Maximum Dry Unit Weight (kN/m^3)	Optimum Moisture Content (%)	Cohesion (kPa)		Effective Friction Angle ϕ' ° (deg)
				As Compacted	Saturated	
***Gravel/Sand Mix*:**						
Well graded, clean	GW	20.0-21.5	8-11	0	0	>38
Poorly graded, clean	GP	18.5-20.0	11-14	0	0	>37
Well graded, minor silt	GM	19.0-21.5	8-12	-	-	>34
Well graded, minor clay	GC	18.5-21.0	9-14	-	-	>31
***Sands/Sandy Soil*:**						
Well graded, clean	SW	17.5-21.0	9-16	0	0	38
Poorly graded, minor silt	SP	16.0-19.0	12-21	0	0	37
Well graded, minor silt	SM	17.5-20.0	11-16	50	20	34
Well graded, minor clay	SC	17.0-20.0	11-19	50	14	33
Low Plasticity Clay/Silt:						
Inorganic silt	ML	15.0-19.0	12-24	75	11	31
Inorganic silt/clay	ML-CL	16.0-19.0	12-22	67.5	9	32
Inorganic clay	CL	15.0-19.0	12-24	65	22	32
Organic silt/clay	OL	13.0-16.0	21-33	85	13	28
High Plasticity Clay/Silt:						
Inorganic silt	MH	11.0-15.0	24-40	72.5	20	25
Inorganic clay	CH	12.0-17.0	19-36	102.5	11	19
Organic clay/silt	OH	10.5-16.0	21-45	-	-	-

Note: *Values apply to Standard Compaction procedure.*

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5.1.3 Rock Strength Parameters

Rock mass classification schemes originally developed for underground excavations have been adapted for surface applications and utilised for estimating rock mass strengths.

The Rock Mass Rating (RMR) or Geomechanics Classification (Bieniawski, 1989) has been adopted in *GALENA*'s Rock Strength from RMR dialog and is based upon the Rock Mass Rating system outlined in Tables 5.2 to 5.5 following. The RMR value is determined from the following parameters – maximum values apply as shown.

Parameter	Maximum Value
Intact Rock Strength (UCS (MPa))	300
Rock Quality Designation (RQD (%))	100
Discontinuity Spacing (mm)	3000
Discontinuity Condition	30
Groundwater	15
Orientation Adjustment	100

The rating adjustment for orientation is based on a percentage reduction of the determined RMR to allow for the influence of dominant structural orientation on the stability of a slope. The suggested adjustments are shown in the table below together with a guide to orientation favourability. This rating adjustment should be used with caution for rock mass strength estimating purposes (Hoek and Brown, 1988).

Relative Orientation		**Adjustment**	
Angle (°) [1]	Description	Slopes	Foundations
70 to 90	Very favourable	100	100
50 to 70	Favourable	80	85
30 to 50	Fair	60	70
10 to 30	Unfavourable	40	55
0 to 10	Very unfavourable	20	40

[1] Defined as the angle between the main defect set and the mean slope angle of the failure surface.

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Note: *The previous table differs from that presented by Bieniawski (1989), which determines the influence by* ***subtraction*** *whereby poorer rock masses may end up with zero or even negative RMR values, which is of little use for slope stability studies.*

The correlation between the RMR value and the Q value (Barton, Lien and Lunde, 1974) is based upon the following relationship (Bieniawski, 1976):

$$RMR = 9 \ln Q + 44$$

As well as determining an RMR value ***GALENA***'s Rock Strength from RMR dialog enables the RMR value to be input directly, if this has been previously determined.

The rock mass strengths in the Rock Strength from RMR dialog are determined according to Bieniawski (1989), Hoek and Brown (1980, 1988) and Krauland et al (1989) in terms of the Mohr-Coulomb c/ϕ parameters.

For the Hoek-Brown failure criteria, values for the constant M_i for intact rock (Hoek-Brown, 1988, Hoek et al, 1992) and the effective normal stress σ_n' are based on the disturbed **m** and **s** parameters (Hoek 1990) which are normally appropriate for excavated rock slopes, as follows:

$$s = \exp \frac{(RMR - 100)}{6}$$

$$\frac{m}{m_i} = \exp \frac{(RMR - 100)}{14}$$

In the absence of laboratory test data an approximate value of M_i can be estimated from the table below for use within the Rock Strength from RMR dialog.

Rock Type	M_i (approx)
Carbonate rocks with well-developed crystal cleavage (dolomite, limestone and marble)	7
Lithified argillaceous rocks [mudstone, shale and slate (normal to cleavage)]	10
Arenaceous rocks with strong crystals and poorly-developed crystal cleavage (sandstone and quartzite)	15
Fine grained polyminerallic igneous crystalline rocks (andesite, dolerite, diabase and rhyotite)	17
Coarse grained polyminerallic igneous and metamorphic rocks (amphibolite, gabbro, gneiss, granite, norite and granodiorite)	25

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In the case of rock mass cohesion determined according to Krauland et al, the original paper is concerned with in-situ underground conditions, and the indicated values of c for any given RMR value are extremely high. As Hoek and Brown's work shows, disturbed rock masses are significantly weaker, and some correction is appropriate to apply to Krauland et al's figures for use in slope stability. An obvious relationship that presents itself is that between the "m" value for disturbed rock masses (as noted above) and that for undisturbed masses.

GALENA therefore determines the ratio of **m** (undisturbed): **m** (disturbed), and divides Krauland et al's original cohesion by this ratio. The resulting value is the cohesion given under the heading "Krauland" in the Rock Strength from RMR dialog. It will be seen that this value is roughly equivalent to those given by Bieniawski and by the Hoek-Brown envelope for reasonable normal stress ranges, which gives certain validity to all of the results.

. The Rock Strength from RMR dialog also presents the average between Krauland and Bieniawski calculated values, and between Hoek-Brown and Bieniawski calculated values, for comparison.

Further information on soil strength parameters and rock mass strength determination can be found within the publications listed in the References section (Section 5.2).

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Table 5.2 The Rock Mass Rating System (Bieniawski, 1989)

Parameter			Ranges of Values						
1	Strength of intact Rock material	Point-load strength index (MPa)	>10	4-10	2-4	1-2	For this low range, uniaxial compressive test is preferred		
		Uniaxial compressive strength (MPa)	>250	100-250	50-100	25-50	5-25	1-5	<1
	Rating		15	12	7	4	2	1	0
2	Drill core quality RQD (%)		90-100	75-90	50-75	25-50	<25		
	Rating		20	17	13	8	3		
3	Spacing of discontinuities		>2 m	0.6-2 m	200-600 mm	60-200 mm	<60 mm		
	Rating		20	15	10	8	5		
4	Condition of discontinuities		Very rough surfaces Not continuous No separation Unweathered wall rock	Slightly rough surfaces Separation <1 mm Slightly weathered walls	Slightly rough surfaces Separation <1 mm Highly weathered walls	Slickensided surfaces *or* Gouge <5 mm thick *or* Separation 1-5 mm Continuous	Soft gouge >5 mm thick *or* Separation >5 mm Continuous		
	Rating		30	25	20	10	0		
5	Groundwater	Inflow per 10 m tunnel length (L/min)	None *or*	<10 *or*	10 -25 *or*	25-125 *or*	>125 or		
		Joint water pressure Ratio ---------- Major principal stress	0 *or*	<0.1 *or*	0.1-0.2 *or*	0.2-0.5 *or*	>0.5 or		
		General conditions	Completely dry	Damp	Wet	Dripping	Flowing		
	Rating		15	10	7	4	0		
Total RMR			100	79	57	34	9		

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Table 5.3 Rock Mass Classes Determined from Total Ratings (Bieniawski, 1989)

RMR Rating	100←81	80←61	60←41	40←21	<20
Class No	I	II	III	IV	V
Description	Very good rock	Good rock	Fair rock	Poor rock	Very poor rock

Table 5.4 Meaning of Rock Mass Classes (Bieniawski, 1989)

Class No	I	II	III	IV	V
Cohesion of the rock mass (kPa)	>400	300-400	200-300	100-200	<100
Friction angle of the rock mass (deg)	>45	35-45	25-35	15-25	<15

Table 5.5 Guidelines For Classification Of Discontinuity Conditions (Bieniawski, 1989)

Parameter	Ratings				
Discontinuity length (persistence/continuity)	*<1 m:* 6	*1-3 m:* 4	*3-10 m:* 2	*10-20 m:* 1	*>20 m:* 0
Separation (aperture)	*None*: 6	*<0.1 mm:* 5	*0.1-1.0 mm:* 4	*1-5 mm:* 1	*>5 mm:* 0
Roughness	*Very rough*: 6	*Rough*: 5	*Slightly rough*: 3	*Smooth*: 1	*Slickensided*: 0
Infilling (gouge)	Hard filling			Soft filling	
	None: 6	*<5 mm:* 4	*>5 mm:* 2	*<5 mm:* 2	*>5mm:* 0
Weathering	*Unweathered*: 6	*Slightly weathered*: 5	*Moderately weathered*: 3	*Highly weathered*: 1	*Decomposed*: 0

Note: *Some conditions are mutually exclusive. For example, if infilling is present, it is irrelevant what the roughness may be, since its effect will be overshadowed by the influence of the gouge. In such cases, use Table 5.2 directly.*

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5.1.4 Using the Rock Strength from RMR Dialog

The Bieniawski Rock Mass Rating (RMR) group of the Rock Strength from RMR dialog provides for input of parameter values for UCS, RQD, Spacing, Condition, Water and Orientation. Values should be entered into all input fields before selecting the Calc (Calculate) button.

Acceptable ranges for each parameter are displayed below each entry field – values outside the acceptable ranges are highlighted and entry of further values blocked. When the Calc button is selected the points derived from input values, the 'Q' value, class rating, description and calculated RMR are displayed.

Further calculation of Hoek-Brown and Mohr-Coulomb parameters require input of an Mi value, and optionally an Sn (effective normal stress (σ_n')) value, within the Hoek-Brown Parameters group before selecting the Calc button within the Hoek-Brown Parameters group. Calculations for Hoek-Brown and Mohr-Coulomb parameters are based on the calculated RMR value displayed within the Bieniawski Rock Mass Rating (RMR) group and in the field below the Bieniawski Rock Mass Rating (RMR) group.

An alternative RMR value may be entered or selected for the field below the Bieniawski Rock Mass Rating (RMR) group. *If an alternative RMR value is found here it is used when the Calc button within the Hoek-Brown Parameters group is selected, in preference to the RMR value shown within the Bieniawski Rock Mass Rating (RMR) group.*

Suggested Mohr-Coulomb parameters (calculated from the user-input values) based on the work of various practitioners are provided as well as some mean values from the same calculations and practitioners

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