r.\textit{rotstab}

Version 2012-06-11

A model for computing the stability of slopes assuming slip circles or ellipsoids based on GRASS \textregistered\ GIS

\textbf{Model outline and manual}

by Martin Mergili

Institute of Applied Geology, BOKU University of Natural Resources and Life Sciences Vienna, Austria
\texttt{martin.mergili@boku.ac.at}
\texttt{www.mergili.at}

in cooperation with Wolfgang Fellin, Ivan Marchesini and Mauro Rossi

\textit{r.rotstab} is a GIS-supported model framework for computing the stability of slopes, assuming ellipsoidal potential slip surfaces. It is designed as raster module for the software \textit{GRASS} GIS. The scientific concepts behind \textit{r.rotstab} are summarized in Chapter 1 (Model outline).

An additional shell script (\textit{r.rotstab.sh}) supports the data management including input of data and parameters as well as post-processing, export and display of the results. Instructions how to operate the model are given in Chapter 2 (Manual).

The model is distributed under the \textit{GNU General Public License (www.gnu.org)}. \textit{r.rotstab} has been created with the purpose to be useful. It has been developed with utmost care. Nevertheless, every user has to be aware that it is only a computer program which functionality may suffer by errors and shortcomings. No responsibility can be taken by the developer for any types of deficiencies in the program or in this document, or for the consequences of such deficiencies.
1 Model outline

1.1 Introduction

GIS-supported analyses of slope stability, landslide susceptibility and landslide hazard have become very common with increased computational power in the last decade (e.g. Van Westen, 2000; Corominas et al., 2003; Guzzetti, 2006; Van Westen et al., 2006). Whilst geostatistical approaches have been applied in some countries (e.g. Lee and Min, 2003; Guzzetti et al., 2006) in order to get a broad picture of hazardous slopes on the local, regional or even national scale, limit equilibrium methods (Duncan, 1996) are chosen for more detailed analyses on the small catchment scale. Such methods relate the shear resistance and the shear force of a slope unit – or a mapping unit such as a GIS raster cell – in order to determine its state of equilibrium, expressed by the safety factor $FS$. Slopes with $FS > 1$ are stable, slopes with $FS < 1$ are unstable. The infinite slope stability model is the most simple application of limit equilibrium techniques for slope stability and is most commonly employed in combination with GIS. It assumes a plane, infinite, slope-parallel failure plane (Fig. 1a) and can be discretized on the basis of GIS raster cells. For a unit raster cell size of $1 \times 1$ m,

$$FS_{inf} = \frac{R}{T} = \frac{c}{W'} + \frac{(W' \cos \beta) \tan \varphi}{W' \sin \beta + F_s}, \quad (1)$$

where $FS_{inf}$ is the safety factor, $R$ and $T$ are the shear resistance and the shear force, $c$ is the cohesion, $A$ is the area of the slip surface of the cell, $W'$ is the weight of the submerged regolith, $\varphi$ is the angle of internal friction, $F_s$ is the seepage force, and $\beta$ is the inclination of the slip surface (see Fig. 1a). Eq. (1) is valid for slope-parallel seepage.

The infinite slope stability model is valid for predicting shallow translational slope failures in rather frictional than cohesive regolith on uniform, plane slopes. It is often coupled with hydraulic models (e.g. Montgomery and Dietrich, 1994; Pack et al., 1998; Wilkinson et al., 2002; Xie et al., 2004b; Godt et al., 2008).

Fig. 1 a Infinite slope stability model b slope stability model based on circular slip surface

However, this type of model is not necessarily suitable for rotational, deep-seated slope instabilities in cohesive regolith or failures of curved or dissected slopes (which can not be seen as „infinite“). Engineers have based their slope stability calculations on various slip surface geome-
tries for many years, most common are slip circles (Fig. 1b). Traditionally, 2D models (longitudinal transects in the direction of the steepest descent) are used. An overview of such approaches is given by Duncan and Wright (2005). The regolith above the slip surface is dissected into a number of columns, and the stabilizing and destabilizing forces or moments are computed for each of them. The summed up values are combined in order to compute the factor of safety. Suitable algorithms were developed e.g. by Fellenius (1927), Bishop (1954) and Janbu et. al (1956). The forces between the columns (see Fig. 1b) are statically unknown in calculations using circular slip surfaces. There are various assumptions to take them into account. The simplest one is to neglect them (Fellenius, 1927). This generally leads to the lowest safety factors (e.g. Kolymbas, 2007).

Using longitudinal sections means that the width of the potential slope failure and the three-dimensional topography of the slope are not accounted for. Since the 1970s, the slope stability algorithms were applied to three-dimensional topographies (Hovland, 1977; Hungr, 1987; Hungr et al., 1989). The leading software package in this respect is CLARA (Hungr, 1988), others are TSLOPE3 (Pyke, 1991) and 3D-SLOPE (Lam and Fredlund, 1993).

The regolith is assumed as rigid body in all above approaches. Calculations with deformable regolith, like finite element slope stability analyses with the strength reduction technique (e.g. Matsui and San, 1992) show various non-circular zones of large shear strain. This gives reasons for using elliptical – or ellipsoidal – slip surfaces (e.g. in the 3D models by Xie et al., 2003, 2004a,c, 2006). Sliding of rigid columns on such surfaces would yield relative displacements between the columns, and therefore the interslice forces could be estimated according to the kinematical elements method (Gussmann, 1982, 1986, 2000). However, the interslice forces are often neglected in these approaches, since this simplifies the computation considerably. It may be assumed that this yields too conservative estimates of the safety factor. Monte-Carlo approaches are frequently used for identifying the most critical slip surface for the area under investigation (Xie et al., 2003, 2004a, c, 2006).

In the beginning of the 21st century, the first attempts to implement three-dimensional slope stability models with GIS packages were made, in particular by Xie et al. (2003, 2004a,c, 2006), Marchesini et al. (2009) and Jia et al. (2012). However, such applications are still severely underrepresented, compared to the infinite slope stability model. In fact, only very few attempts to compare the infinite slope stability model to three-dimensional models have been published. Griffiths et al. (2011) found out that the infinite slope stability model is suitable for landslide length to depth ratios $L/D>16$, Milledge et al. (in press) reported a threshold of $L/D = 25$ above which these models are unconditionally applicable. However, also topography decides upon the suitability of the one or the other model (Mergili and Fellin, in press).

The work presented here is seen as an attempt to integrate a three-dimensional slope stability model based on ellipsoidal slip surfaces with a raster-based Open Source Geographic Information System (GRASS GIS; Neteler and Mitasova, 2007; GRASS Development Team, 2011), in order to allow for the spatially distributed analysis of slope stability going beyond the infinite slope stability model.

1.2 The model r.rotstab

1.2.1 General model layout

The Open Source software package GRASS GIS builds on a flexible modular design with modules for general operations, raster and vector analysis, display and more (GRASS Development Team, 2011). Modules can be added by individual developers, so that the standard GIS functions (e.g. r.mapcalc for raster calculations) are complemented by a large array of more specialized applications. Such applications can be used individually or made available to the community by adding them to the modules distributed with the download of GRASS GIS. Examples of landslide-related models implemented with GRASS GIS are r.debrisflow (Mergili et al., 2012a) and r.avalanche (Mergili et al., 2012b). The three-dimensional slope stability model was implemented as raster module r.rotstab. It is based on the programming language C. Data management and display is facilitated by a shell script. The program requires a digital elevation model, the water content $\theta$ as well as the regolith parameters for each layer (cohesion $c$, angle of inter-
nal friction $\varphi$, dry specific weight $\gamma_d$) and the depth of each layer $d$ as input. The entire work flow of r.rotstab is illustrated in Fig. 2 and detailed in the following section.

![Fig. 2 Work flow of r.rotstab](image)

### 1.2.2 Selection of slip surfaces

r.rotstab works with ellipsoidal slip surfaces, defined by the coordinates of the centre, the lengths of the three half axes ($a_e$, $b_e$ and $c_e$), aspect $a$, and inclination $\beta$ (Fig. 3). The maximum length of the potential landslide body $L$ is expressed along the main inclination direction of the ellipsoid, the width $W$ runs perpendicular to $L$ and the depth $D$ is expressed in vertical direction.

![Fig. 3 a Ground plot b longitudinal section of an arbitrary slip ellipsoid](image)

The model offers two ways for selecting the parameters:

- The slope stability calculation is run with user-defined parameters for one single slip surface. This layout is suitable for the analysis of one specific landslide body with a known depth of the slip surface, e.g. for the back-calculation of a previous event.
- The computation is run for a user-defined number of times, each time using an ellipsoid with randomly determined coordinates of the centre of the ellipsoid, lengths of $a_e$, $b_e$, $c_e$ and offset of the centre from the terrain $z_b$. The maxima and minima of landslide length $L$, width $W$, the ratio $L/W$ and depth $D$ as well as of $z_b$ are defined by the user in order to constrain the randomization. This layout is suitable if the most critical slip surface is not a priori known, e.g. for landslide susceptibility analyses at the small catchment scale.
- Four reference points are set at distances of $r/a_e$ from the centre, where $r$ is defined randomly for each ellipsoid, constrained by $0.5 < r/a_e < 1.0$ (see Fig. 3). The slope and aspect of the terrain are derived from these reference points. $a$ and $\beta$ are determined in the way that $a$ follows the steepest slope and $c$ is aligned perpendicular to the terrain surface.
### 1.2.3 Computation of the 3D safety factor

This step is performed separately for each slip surface. First, the ellipsoid is transformed from its internal coordinate system into the GIS coordinate system. r.rotstab includes the option to test also truncated circles or ellipsoids which can be critical in the presence of weak layers or hard bedrock. This concept follows Xie et al. (2004a), where weak layers or discontinuities within the ellipsoid are considered as possible slip surfaces. As a consequence, more than one slip surface may be associated with each ellipsoid. On the other hand, several truncated ellipsoids may intersect the same sliding surface.

The 3D safety factor $FS_{3D}$ is derived according to the 3-dimensional modification of the column-based Hovland (1977) model (Xie et al., 2003, 2004a, c, 2006). In contrast to the Bishop (1954) and Janbu et al. (1956) models, the safety factor is computed directly, without an iteration procedure. The horizontal components of the shear resistance and the shear force are summed up over all columns. Each column corresponds to one raster cell in the GIS. Compared to the original models of Hovland (1977) and Xie et al. (2003, 2004a, c, 2006), an improved approximation of the seepage force is included:

$$FS_{3D} = \frac{\sum c (cA + (W\cos\beta_c + N_s)\tan\varphi)\cos\beta_m}{\sum c (W\sin\beta_m + T_s)\cos\beta_m},$$

(2)

where $c$ is the cohesion, $A$ is the area of the slip surface of the considered column, $\varphi$ is the angle of internal friction, and $W$ is the weight of the regolith column down to the slip surface. For saturated regolith, the submerged weight is used. $\alpha$ stands for horizontal angles (aspect), $\beta$ stands for vertical angles (inclination).

The direction of the shear resistance is prescribed by the friction, acting along the steepest slope of the slip surface of the considered column (defined by $\alpha_c$ and $\beta_c$; Fig. 4a). The shear force acts along the main aspect of the ellipsoid $\alpha$ (see Fig. 3). $\beta_m$ is the apparent dip of the slip surface at the considered column in the direction of $\alpha$ (see Xie et al., 2003).

$$\tan\beta_m = \tan\beta_c \cos(\alpha_c - \alpha).$$

(3)

$N_s$ and $T_s$ in Eq. (2) are the contributions of the seepage force to the shear resistance and the shear force. The seepage force acts in the direction of the hydraulic gradient which is here approximated by the aspect and slope of the groundwater level ($\alpha_w$ and $\beta_w$; see Fig. 4b):

$$F_s = \gamma_w dx \cdot dy \cdot d_{sub} \sin\beta_w,$$

(4)

where $\gamma_w$ is the specific weight of water, $dx$ and $dy$ are the raster cell sizes in $x$ and $y$ direction, and $d_{sub}$ is the depth of the submerged regolith. The horizontal component $F_{s,h}$ and the vertical component $F_{s,v}$ of the seepage force are

$$F_{s,h} = F_s \cos\beta_w, \quad F_{s,v} = F_s \sin\beta_w.$$

(5)

$F_{s,v}$ is invariant in terms of the projection of $F_s$ to any vertical plane. Therefore only the horizontal component has to be projected to the vertical planes defined by the steepest slope ($\alpha_c$ and $\beta_c$) and the main inclination direction of the slip surface ($\alpha_{ch}$ and $\beta_{ch}$): $F_{s,\alpha_{ch}} = F_{s,h} \cos(\alpha_w - \alpha_c)$. $F_{s,mh} = F_{s,h} \cos(\alpha_w - \alpha)$. The projected seepage forces $F_{s,c}$ and $F_{s,m}$ and their vertical angles $\beta_{Fs,c}$ and $\beta_{Fs,m}$ are then derived as follows:

$$F_{s,c} = \sqrt{F_{s,v}^2 + F_{s,\alpha_{ch}}^2}, \quad F_{s,m} = \sqrt{F_{s,v}^2 + F_{s,mh}^2},$$

(7)

$$\cos\beta_{Fs,c} = F_{s,\alpha_{ch}}/F_{s,c}, \quad \cos\beta_{Fs,m} = F_{s,mh}/F_{s,m}.$$

(8)

The component of $F_{s,c}$ perpendicular to the slope represents the contribution of the seepage force to the shear resistance $N_s$, the slope-parallel component of $F_{s,m}$ represents the contribution of the seepage force to the shear force $T_s$ (see Eq. 2):

$$N_s = F_{s,c} \sin(\beta_{Fs,c} - \beta_c),$$

(9)

$$T_s = F_{s,m} \cos(\beta_{Fs,m} - \beta_m).$$

(10)

For now, additional forces or seismic loads are not considered (see Xie et al., 2006).
1.2.4 Discretization of the results for each slip surface

After repeating the slope stability calculation for each slip surface, the model results are discretized to the GIS raster cells. Any raster cell may be intersected by various slip surfaces, each associated with a safety factor. This results in an overview of potentially unstable regions without showing the individual sliding areas. The following sets of output raster maps are produced (see Fig. 2):

- The minimum factor of safety applicable to each raster cell $FS_{\text{min}}$ and the depth of the associated slip surface.
- The deepest slip surface with $FS_{3D} < 1$ and the corresponding factor of safety.
- A measure for landslide susceptibility, based on a weight depending on the safety factor, $w_{FS}$:

  \[
  \begin{align*}
  \text{if } (FS_{\text{min}} > 1.2) w_{FS} &= 0 \\
  \text{else if } (FS_{\text{min}} > 0.8) w_{FS} &= 2.5(1.2 - FS_{\text{min}}) \\
  \text{else } w_{FS} &= 1
  \end{align*}
  \] (11)

  
- Summing up $w_{FS}$ over all tested ellipsoids and dividing the result by the total number of ellipsoids touching the considered raster cell gives an estimate of landslide susceptibility. Even though, strictly spoken, only the most critical slip surface is decisive for slope stability, the geotechnical parameters – and particularly their spatial patterns – are often uncertain so that considering only the result for the one most critical slip surface may not be enough.

Furthermore, a table with the ellipsoid parameters and the factor of safety for each slip surface is generated.

The infinite slope stability model is run independently of the three-dimensional model. The factor of safety is computed for each raster cell and each regolith layer according to Eq. (1). Also here, the lowest factor of safety and the deepest slip surface with $FS_{3D} < 1$ are stored.
1.3 References


2 Manual

2.1 System requirements

*r.rotstab* was developed and tested under *Ubuntu 12.04 LTS* with *GRASS 6.4*. It probably works on most other *UNIX* systems as well as with other versions of *GRASS*.

Please make sure to have a proper installation of *GRASS* before installing *r.rotstab*. *GRASS* has to be installed from source, not from a binary. In case of doubt, consult [www.grass.fbk.eu](http://www.grass.fbk.eu).

2.2 File management

The file system *r.rotstab* consists of two parts:

- a *GRASS* mapset with all the spatially distributed input information as raster and vector maps (the units used in the mapset have to be metres), and
- a folder named *r.rotstab* which may be stored at any location of your *home* directory. The internal structure of the folder *r.rotstab* may not be manipulated, otherwise the functionalities are not given any more.

The directory *r.rotstab* contains the following subdirectories:

*tools*

The *tools* directory hosts the scripts required for installing and running *r.rotstab*:

- *main.c*: the source code for *r.rotstab*;
- *r.rotstab.sh*: a shell script for data input, management and output;
- *r.rotstabxl.sh*: the same shell script for data input, management and output, but for large datasets (the region is divided into a user-defined number of tiles);
- and *install.sh*: a shell script helping to compile the source code (*main.c*).

*data*

It contains the parameter file (*test_param.txt* as part of the test dataset, other parameter files can be created as needed). Please note that the structure of the parameter file is fixed and may not be changed. However, the number of soil classes and the number of layers for each soil class may be adopted. The subfolder *colours* contains colour tables for the display of the results.

*temp*

The *temp* directory contains temporary files created during the execution of *r.rotstab.sh*. Its content shall not be manipulated manually, but only using the functionalities of *r.rotstab.sh*.

*results*

It contains the summary file of the simulation results. However, the main results are stored as rasters in the active *GRASS* mapset.

2.3 Installation

*r.rotstab* has to be added to the *GRASS* raster library as a new module, based on the source code of the file *main.c*. For performing this task, call the script *install.sh* in the folder *r.rotstab/tools*:

```
cd dir/r.rotstab/tools
sudo sh install.sh
```

*dir* may be any location in your *home* directory. First, you have to specify your password in order to be allowed to run the script. Then, the following prompt is displayed:
Full path to GRASS source (slashes at beginning and end):

Enter the path to the GRASS source, e.g. /usr/local/src/grass64_release/, but not to the place where GRASS is installed. The slashes at the beginning and the end of the path are required. The Makefile is created, and compilation and installation are run automatically, so that \texttt{r.rotstab} is ready to use.

Please note that you have to change to the tools directory as described above – if just entering

\begin{verbatim}
sh dir/r.rotstab/tools/install.sh
\end{verbatim}

an error message will display and \texttt{r.rotstab} will not be installed.

2.4 Test dataset

A test dataset is provided together with the program, consisting of some text files and a GRASS location with the name \texttt{test_rotstab} (mapset \texttt{test_rotstab_maps}). The data has a spatial extent of 9200 x 7000 m, the default resolution is 10 m. All data are packed in the file \texttt{testdata.zip}.

The digital elevation model was extracted from www.viewfinderpanoramas.org, the landslide inventory from the IFFI dataset, both datasets were modified and shifted. Table 1 shows the names of the raster and vector maps within the mapset \texttt{test_rotstab_maps}. In addition, a parameter file named \texttt{test.param.txt} is provided in the folder \texttt{data}. It assumes two soil classes with two layers each, corresponding to the soil classes defined by the raster \texttt{test_soilclass} (Fig. 5).

The file \texttt{test_tiles.txt} defines the tiles required to run \texttt{r.rotstabxl.sh}.

A general rule of thumb: when applying \texttt{r.rotstab.sh}, the model can be run at a cell size of 40 m or coarser, with \texttt{r.rotstabxl.sh} the model can be run at a cell size of 10 m or coarser. However, this also depends on the processor used. When running \texttt{r.rotstab} at a too fine cell size, a segmentation fault occurs.

Table 1 Names of the maps of the test dataset

<table>
<thead>
<tr>
<th>name of map</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>test_elev</td>
<td>elevation map (raster)</td>
</tr>
<tr>
<td>test_soilclass</td>
<td>soil classes map (raster)</td>
</tr>
<tr>
<td>test_depth1</td>
<td>depth of bottom of soil layer 1 (raster)</td>
</tr>
<tr>
<td>test_depth2</td>
<td>depth of bottom of soil layer 2 (raster)</td>
</tr>
<tr>
<td>test_observed</td>
<td>observed slope failures (vector)</td>
</tr>
</tbody>
</table>

Fig. 5 The test dataset (shaded relief and landslide inventory)
2.5 Data management

\textit{r.rotstab} uses text files and rasters with predefined names as input. The shell scripts \textit{r.rotstab.sh} or \textit{r.rotstabxl.sh}, respectively, serve for creating these datasets. \textit{r.rotstab.sh} and \textit{r.rotstabxl.sh} offer the following modules:

\begin{enumerate}
\item 1 --> Input
\item 2 --> Execution of simulation
\item 3 --> Post-processing of model output
\item 4 --> Display of results
\item 5 --> Removal of result files
\item 6 --> Cleaning of file system
\item 7 --> Exit
\end{enumerate}

When entering a number, the corresponding module is executed. \textit{r.rotstab.sh} and \textit{r.rotstabxl.sh} have to be called from within the \textit{GRASS} mapset with all the required raster maps.

2.5.1 Input

\textit{Module 1} consists of a sequence of prompts for input of data and parameters (Table 1). If no input is given for a prompt (by just pressing \textit{ENTER}), the dataset specified earlier is kept.

- \textit{Parameter file (text file, required)}:

  Text file with list of parameters for the simulation. It includes geotechnical and hydraulic parameters as well as ellipsoid simulation parameters. The parameters have to be specified in an exactly defined order (please use \textit{test_param.txt} as reference).

  The numbers of the soil classes specified in the parameter file have to correspond to the numbers in the raster map defining the spatial distribution of the classes. Each class in the raster map requires an entry in the parameter file. Soil classes specified in the parameter file but not in the raster map are neglected.

  For each soil class the depth, geotechnical and hydraulic parameters of each layer have to be specified. Numbering of the soil layers is always from the top to the bottom. Table 2 provides a description of the parameters. Soil classes with numbers from 1 to 100 and maximum 10 layers for each soil class are supported. There is no separate entry of the groundwater table which is derived from the water content of the soil layers (see also Section 2.6). Therefore, also multiple groundwater layers can be managed.

  The depth of each soil layer may alternatively be read from raster maps instead of the parameter file. If this is desired, the value -9999 has to be entered instead of the respective depth (it is sufficient to do this for the first layer of the first soil class). Then, the program prompts for maps depicting the depth of each layer (always related to the soil surface). The number of layers for which a depth is specified has to match the maximum number of layers from all soil classes.

Table 2 Soil parameters required for each layer

<table>
<thead>
<tr>
<th>shortcut</th>
<th>unit</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>weight</td>
<td>N / m³</td>
<td>specific weight of the soil in dry condition</td>
</tr>
<tr>
<td>csoil</td>
<td>N / m²</td>
<td>soil cohesion</td>
</tr>
<tr>
<td>phi</td>
<td>degree</td>
<td>angle of internal friction</td>
</tr>
<tr>
<td>theta</td>
<td>vol.-per cent</td>
<td>water content of the soil layer</td>
</tr>
<tr>
<td>depth</td>
<td>m</td>
<td>depth of the bottom of the layer related to the soil surface (optional, may also be read from raster map – in this case, a value of -9999 has to be specified in the parameter file)</td>
</tr>
</tbody>
</table>

The landslide and ellipsoid parameters to be constrained are illustrated in Figure 1 (units are metres or ratios, respectively). If the maximum width of the landslide is set to -9999, the b and c axes are set to the same length as the a axis, resulting in a spherical slip surface. If the coordinates of the centre of the ellipsoid are set to -9999, a random procedure to determine the coordinates is performed when executing the simulation. In this case it is useful to
set the number of simulations to a very high value (depending on the size of the study area) in order to figure out the most critical case. This procedure should be applied if the location and geometry of the most critical slip surface is not a priori known. If coordinates (in the coordinate system of the mapset used) are specified, the number of simulations should be set to 1. This makes sense if the location and geometry of the slip surface are known.

If the parameter truncated ellipsoid allowed is set to 1, the layer interfaces are considered as potential slip surfaces, otherwise only the ellipsoid is considered.

• --> Tiles file (text file, required):

This prompt only applies if r.rotstabxl.sh is used. The main computation is performed separately for each tile, allowing the coverage of large areas without running into troubles with the memory. The results for each tile are merged automatically. The northern, southern, western and eastern boundaries of each tile are specified, please keep exactly to the structure demonstrated in test_tiles.txt. The tiles have to be defined manually, please be aware that they should overlap by one landslide maximum length or width, depending on the larger value.

• --> Observed landslide scarps (line vector, optional):

A line vector map with areas of slope failure observed in the field may be specified, if available, for facilitating the evaluation of the model results (test dataset: test_observed).

• --> Elevation map (m, required):

Raster map of surface elevation (metres).

• --> Soil classes map (nominal, required):

Integer raster map defining the spatial distribution of the soil classes specified in the soil parameter file.

• --> Soil depth maps for each layer (m, required)

layer 1:

Raster map defining the depth of each soil layer, related to the soil surface. The prompt only appears if the depths of the layers are not specified in the parameter table. The depth rasters have to be entered from top to bottom, separated by pressing ENTER.

2.5.2 Execution of simulation

A prompt for cell size displays:

--> Cell size for simulation (m):

The cell size has to be chosen in accordance with the input datasets and the required level of detail. For test simulations it is recommended to choose larger cell sizes in order to reduce computing time. The GRASS raster module r.rotstab is then called by pressing ENTER. The model is run as described in Chapter 1. Only those ellipsoids which are entirely located within the area where soil classes are defined are considered, the number of valid ellipsoids is shown on the screen as soon as the simulation is completed. Furthermore, the infinite slope stability model is implemented in the code providing factors of safety and potential slip surfaces for each pixel.

Additionally to a number of raster maps which are listed in detail in Table 3, a summary file (summary.txt) is written and stored in the dir/r.rotstab/results/ directory. The summary file lists the geometric parameters of each ellipsoid and the resulting factor of safety. The last line of the summary file shows the parameters for the most critical of all tested ellipsoids. The contents of the summary file are also displayed in the terminal while the computation is running. The abbreviations used in the header line are explained in Table 4.
2.5.3 Post-processing of model output

All the resulting raster maps are cleaned (cells outside of the defined mask are set to no data) and colour tables are assigned to the factor of safety map and the potential depth of failure map for each time step. The colour tables are stored in dir/r.rotstab/data.

Table 3 Output raster maps produced by r.rotstab

<table>
<thead>
<tr>
<th>shortcut</th>
<th>unit</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>r_fos_min</td>
<td>–</td>
<td>minimum factor of safety for each pixel</td>
</tr>
<tr>
<td>r_cumfos_crit</td>
<td>–</td>
<td>weight for landslide susceptibility, cumulated over all tested ellipsoids</td>
</tr>
<tr>
<td>r_cumsurf</td>
<td>–</td>
<td>number of tested ellipsoids</td>
</tr>
<tr>
<td>r_critrat</td>
<td>–</td>
<td>weight for landslide susceptibility, averaged over all tested ellipsoids</td>
</tr>
<tr>
<td>r_fos_deep</td>
<td>–</td>
<td>factor of safety &lt;1 with the deepest slip surface for each pixel</td>
</tr>
<tr>
<td>r_depthfail_min</td>
<td>m</td>
<td>slip surface with lowest factor of safety for each pixel</td>
</tr>
<tr>
<td>r_depthfail_deep</td>
<td>m</td>
<td>deepest slip surface with factor of safety &lt;1 for each pixel</td>
</tr>
<tr>
<td>r_depthfail_crit</td>
<td>m</td>
<td>most critical slip surface</td>
</tr>
<tr>
<td>r_lmin</td>
<td>m</td>
<td>length of a half axis of ellipsoid with minimum factor of safety</td>
</tr>
<tr>
<td>r_wmin</td>
<td>m</td>
<td>length of b half axis of ellipsoid with minimum factor of safety</td>
</tr>
<tr>
<td>r_zbmin</td>
<td>–</td>
<td>offset of centre of ellipsoid from terrain, related to the c half axis</td>
</tr>
<tr>
<td>r_fos_infin_min</td>
<td>–</td>
<td>minimum factor of safety (inf. slope stability model)</td>
</tr>
<tr>
<td>r_fos_infin_deep</td>
<td>–</td>
<td>factor of safety &lt;1 with the deepest slip surface (inf. slope stability model)</td>
</tr>
<tr>
<td>r_depthfail_infin_min</td>
<td>m</td>
<td>slip surface with lowest factor of safety (inf. slope stability model)</td>
</tr>
<tr>
<td>r_depthfail_infin_deep</td>
<td>m</td>
<td>deepest slip surface with factor of safety &lt;1 (inf. slope stability model)</td>
</tr>
</tbody>
</table>

Table 4 Legend to the summary file produced by r.rotstab

<table>
<thead>
<tr>
<th>shortcut(s)</th>
<th>unit</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ell</td>
<td>–</td>
<td>number of ellipsoid</td>
</tr>
<tr>
<td>x0, y0</td>
<td>m</td>
<td>coordinates of centre of ellipsoid</td>
</tr>
<tr>
<td>a, b, c</td>
<td>m</td>
<td>lengths of half axes of ellipsoid</td>
</tr>
<tr>
<td>zb</td>
<td>m</td>
<td>offset of centre of ellipsoid from terrain</td>
</tr>
<tr>
<td>fit</td>
<td>–</td>
<td>ratio of a half axis length used for rotation of ellipsoid</td>
</tr>
<tr>
<td>alpha, beta</td>
<td>degree</td>
<td>rotation angles of ellipsoid around its z and y axes</td>
</tr>
<tr>
<td>L, W, A, D</td>
<td>m, m²</td>
<td>length, width, area and maximum depth of slip surface (see Fig. 3)</td>
</tr>
<tr>
<td>fos</td>
<td>–</td>
<td>factor of safety computed for slip surface</td>
</tr>
<tr>
<td>fos1, fos2 etc.</td>
<td>–</td>
<td>factors of safety for the bottom of each soil layer (only if truncated slip surfaces are allowed, see Figure 2)</td>
</tr>
<tr>
<td>time</td>
<td>s</td>
<td>time needed for the computation</td>
</tr>
</tbody>
</table>

Furthermore, the resulting raster maps are exported as ascii rasters in order to enable display in other software packages. These rasters are stored in the folder dir/r.rotstab/results/asc.

2.5.4 Display of results

The results of the simulation can be visualized using this module. The following parameters have to be specified:

- **--> Azimuth of the sun for shaded relief map (degree):**

  All maps are displayed with a shaded relief in the background, the azimuth of which has to be specified (in decimal degrees; recommended value for most areas: 315).

- **--> Export of maps to png (boolean)?**

  The displayed maps can be automatically stored as png in dir/r.rotstab/results/png. If you wish to do so, please enter 1, otherwise 0.
• --> Height of monitor (pixels):

Please specify the height of the monitor for display – a value between 500 and 800 is recommended, depending on the size of your monitor.

After all parameters have been entered, a monitor opens and the maps \( r_{\text{fos min}} \), \( r_{\text{depthfail deep}} \), \( r_{\text{critrat}} \) and \( r_{\text{fos infin min}} \) are displayed in a defined sequence – please press \textit{ENTER} in order to proceed to the next map. After the last map, the monitor closes and the main menu appears in the terminal.

If you have chosen to export the maps as \textit{png}, no prompts appear, all maps are displayed and exported automatically without pressing \textit{ENTER} in between.

2.5.5 Removal of result files

All results (rasters and text files produced by \textit{r.rotstab} and \textit{Module 4}) are deleted. All temporary files created in \textit{Module 1} are kept, so that new simulations may be performed immediately.

2.5.6 Cleaning of file system

All temporary rasters and text files created in \textit{Module 1} are deleted. \textit{Module 1} must be re-run in order to perform new simulations.

2.5.7 Exit

\textit{r.rotstab.sh} or \textit{r.rotstabxl.sh} is exited and the default cell size is restored.

2.6 Known deficiencies of the model

There are two known issues the user has to be aware of when running the model. These deficiencies shall be attacked in the future development of \textit{r.rotstab}:

• Even though the model is able to deal with multiple ground water layers, in its current version it is not able to deal with partly saturated soils. As soon as the water content of a layer is set to a value larger than 0, this layer is considered as saturated.

• Regarding the display of the results, the placement of some of the map elements (legend, scale bar) are not suitable for all scales and map formats. It may happen that some of the legend parameters or placement options have to be changed in the shell script \textit{r.rotstab.sh} itself in order to achieve satisfactory layouts.

The users are encouraged to report further bugs, errors or deficiencies of the model \textit{r.rotstab} to martin.mergili@boku.ac.at.