

r.rotstab: a GRASS-based deterministic model for deep-seated landslide susceptibility analysis over large areas

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Landslides can be studied at site scale (i.e. for individual slopes) or at large (local) or small (regional) scales [1,2]. The deterministic approaches to the landslide stability assessment at site scales are quite classical and commonly accepted procedures. The deterministic analysis of landslides at local and regional scales (distributed models), and the relative estimation of landslide susceptibility, are non-standard tasks.

Deterministic slope stability models, based on limit equilibrium analysis, are applied to particular landslide types (e.g., shallow soil slips, debris flows, rock falls), or to investigate the effects of specific triggers, i.e., an intense rainfall event or an earthquake. In particular, distributed infinite slope stability models are used to evaluate the spatial probability of shallow slope failures. In these models, the factor of safety is computed on a pixel basis, assuming a slope-parallel, infinite slip surface. They can be easily implemented in GIS environments since they do not rely on complex neighborhood relationships.

However, since shallow slope failures coexist locally with deep-seated landslides, infinite slope stability models fail to describe the complexity of the landslide phenomena. Limit equilibrium models with curved sliding surfaces are geometrically more complex, and their implementation with raster-based GIS is a challenging task. Only few attempts were made to develop GIS-based three-dimensional applications of such methods [3].

We present a preliminary implementation of a GRASS GIS-based, three-dimensional slope stability model capable of dealing with both shallow and deep-seated slope failures.

The Open Source GIS package GRASS GIS [4] environment offers comprehensive opportunities for spatial analysis, particularly raster operations. Simple analyses or standard procedures can be performed using the existing tools or combining them by shell scripting. More complex tasks or non-standard procedures can be performed by implementing new modules, making use of the Python or C languages.

The model is developed and evaluated in GRASS GIS 6.4 version as the C-based raster module r.rotstab. Data management is facilitated by the shell script r.rotstab.sh. For large study areas the program includes the option to split the area into a number of tiles, to run the computation separately for each tile and at the end to combine the results for each tile (script r.rotstabxl.sh). This avoids running into troubles with limited memory and allows to largely rely on ordinary arrays instead of segmentation files, which would considerably slow down the computation process. There has to be an overlap of the maximum extent of one ellipsoid between the tiles in order to avoid poorly covered areas at the edges.

The model makes use of a slight modification of the three-dimensional sliding surface model proposed by Hovland [5] and revised and extended by Xie et al. [3]. Given a Digital Elevation Model (DEM) and a set of thematic layers, mainly concerning geotechnical and hydraulic parameters, the model evaluates the slope instability over a large number of randomly determined potential ellipsoidal slip surfaces. In addition to ellipsoidal slip surfaces, truncated ellipsoids can be used to simulate the presence of shallow weak layers, delimited by soil discontinuities or hard bedrock. Any raster cell may be intersected by various sliding surfaces, each associated with a computed factor of safety. The lowest value of the factor of safety is stored for each raster cell together with the depth of the associated slip surface. This results in an overview of potentially unstable regions without showing the individual sliding areas. In addition, a landslide susceptibility index in the range 0 - 1 is provided, relating the number of unstable slip surfaces to the total number of slip surfaces simulated in each pixel.

We test the model in the Collazzone area, Umbria, Central Italy, which is susceptible to landslides of different types. The presence of both shallow translational and deep-seated

rotational landslides and the availability of reference data allow for the critical evaluation of the model in comparison with infinite slope stability models.

For the calculation the entire Collazzone area is split into 150 tiles of approx. 1.7 x 1.6 km and 500,000 ellipsoids were simulated for each tile.

Exploiting slip surfaces truncated at a depth of 1.3 m - the average depth of shallow landslides recorded in the area - the model successfully predicts the observed landslides patterns. As expected for this type of landslides, the results are in general very similar to those yielded with the infinite slope stability model. However, the results yielded with r.rotstab are more smoothed since small-scale variations of topography (particularly slope) are smoothed out. Both models result in a significant number of false positive raster cells (i.e. stable cells, wrongly predicted as unstable), which may either be areas potentially affected by landslides in the future, or mispredictions due to insufficient parameter knowledge. Tuning the geotechnical parameters towards a lower number of false positives can only be done at the cost of an increased number of false negative raster cells, which are certainly mispredictions.

Whilst this problem is moderate for shallow landslides, it is more pronounced for deep-seated landslides reaching a maximum depth of 20 m in the Collazzone area. In that case, the distribution of the observed landslides is very likely to be conditioned also by factors not used - or not accounted for appropriately - in the model.

Since r.rotstab is designed specifically for this type of landslides, one of the main future tasks will be to explore further key parameters influencing deep-seated slope stability. For example the bedding attitude of the geological layers is supposed to be one of the most important aspects that condition the slope stability. According to field observations in the Collazzone area, morpho-structural settings play a crucial role for deep-seated landslide distribution. A second key for improving the prediction rate will be to refine the knowledge on the spatial (particularly vertical) structure of the regolith parameters.

Besides the collection and preparation of additional data, more advanced and extended parameter tests will also be required to improve the model performance.

Using a Virtual Machine (1 core - 3.00GHz, with 8 Gb of RAM) running Ubuntu 11.04, the current implementation is able to process several tens of millions ellipsoids per day. Further enhancement of the model performance will require the parallelization of the code in order to run in multiple core environments or on a grid infrastructure (cloud computing). For this purpose we intend to test the module r.cloud which will be part of the prospective release of GRASS 7 in the near future.

References

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Keywords: cloud computing, Collazzone area, factor of safety, GRASS GIS, slip ellipsoid, slope stability model

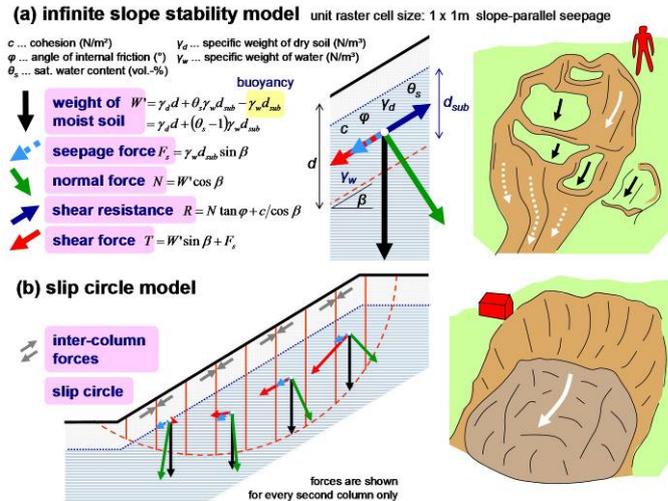


Figure 1 - Infinite slope stability model and slip circle model

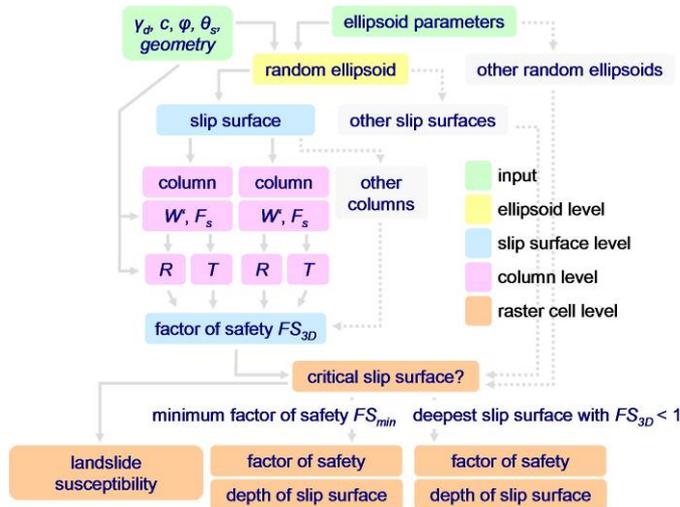


Figure 2 - Work flow of r.rotstab

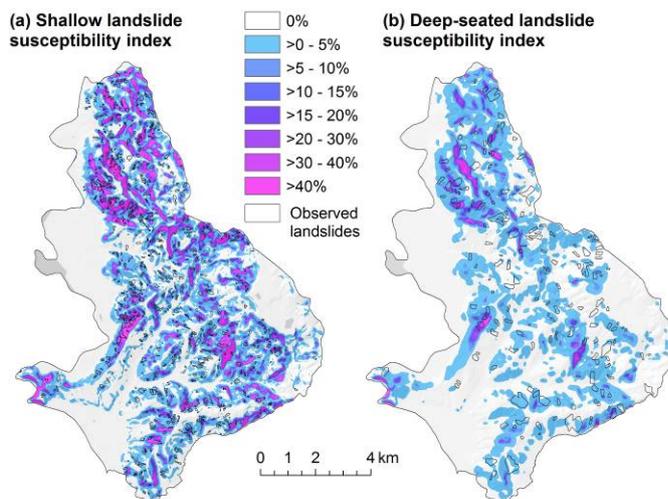


Figure 3 - Landslide susceptibility indices for shallow and deep-seated landslides