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Spatially distributed three-dimensional slope stability modelling in a raster GIS

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ABSTRACT

We present a GRASS GIS implementation of a three-dimensional slope stability model capable of dealing with shallow and deep-seated slope failures, *r.rotstab*. It exploits a modified version of the revised Hovland method and evaluates the slope stability over a large number of randomly selected slip surfaces, ellipsoidal or truncated in shape. For each raster cell in the modelling domain, the factor of safety is taken from the most critical slip surface. This results in an overview of potentially unstable regions without showing the individual sliding areas. Furthermore, the model produces a susceptibility index for each cell, based on the proportion of slip surfaces with a low factor of safety. We test the model in the Collazzone area, Umbria, central Italy where detailed information on shallow and deep-seated landslides, morphology and lithology is available. The rate of true predictions (landslide plus non-landslide) ranges from 54.7 to 81.2% for shallow landslides and from 58.5 to 87.4% for deep-seated landslides, depending on the adjustment of the uncertain geotechnical parameters. In the same order, the rate of true landslide predictions decreases from 80.2 to 19.9% (shallow) and from 64.3 to 3.6% (deep-seated) so that an increase of the true landslide prediction rate can only be achieved at the cost of a significant increase of the false alarm rate. The results for shallow landslides are very similar to those yielded with the infinite slope stability model in terms of the minimum factor of safety, but differ substantially in terms of the spatial patterns. The evaluation of the landslide susceptibility index yields areas under the ROC curves of 0.68–0.70 (shallow landslides, *r.rotstab*), 0.61–0.65 (shallow landslides, infinite slope stability model) and 0.59–0.63 (deep-seated landslides). We conclude that the *r.rotstab* model outperforms the infinite slope stability model.

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1. Introduction

Modelling of landslide susceptibility can be accomplished using a variety of approaches, including statistical, physically-based, and geotechnical approaches (Guzzetti et al., 1999; Van Westen, 2000; Guzzetti, 2006; Van Westen et al., 2006). Modelling of the spatial probability (i.e., the susceptibility) of shallow landslides for small catchments often makes use of deterministic, physically-based models (Van Westen et al., 2006). These modelling approaches rely mainly on infinite slope stability models coupled with more or less complex hydrological and infiltration models (e.g., Wilkinson et al., 2002; Muntohar and Liao, 2010). The distributed models for slope stability, hydrology and infiltration are simple to implement in a Geographic Information System (GIS) environment, and specifically in a raster-based GIS (Montgomery and Dietrich, 1994; Burton and Bathurst, 1998; Pack et al., 1998; Baum et al., 2008). This has eased their widespread distribution and application in different environmental, physiographical and climatic settings (Van Westen and Terlien, 1996; Xie et al., 2004a; Godt et al., 2008; Mergili et al., 2012).

In many landscapes, shallow slope failures coexist with deep-seated mass movements (e.g., Guzzetti et al., 2004; Zêzere et al., 2005; Guzzetti et al., 2006a). The infinite slope stability model, building the base of many spatially distributed susceptibility assessments of shallow slope failures, fails to capture the complexity of the deep-seated landslide phenomena. In order to evaluate the stability conditions of deep-seated landslides, more advanced limit equilibrium models capable of accounting for the complex geometry of the deep-seated failures should be used. However, the GIS implementation of limit equilibrium models for deep-seated failures remains a challenging task, limiting the spatially distributed modelling of deep-seated landslides.

In this work, we present the results of an attempt to integrate a three-dimensional limit equilibrium slope stability model in the open source Geographic Resources Analysis Support System (GRASS) raster GIS (Neteler and Mitasova, 2007; GRASS Development Team, 2011). The paper is organized as follows. In Section 2, we summarize the rationale for using the limit equilibrium model. In Section 3, we introduce *r.rotstab*, a computer model for the three-dimensional, spatially distributed modelling of slope stability in a raster GIS. This is

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followed by a description of the Collazzone study area, Umbria, central Italy, where the *r.rotstab* model was tested (Section 4), and by a description of the landslide and environmental data available for the study area (Section 5). Next, we present (Section 6) and discuss (Section 7) the results obtained for shallow and deep-seated landslides and the model performance in the study area. We conclude (Section 8) by summarizing the main results obtained.

2. Background

Slope stability calculations often rely on the limit equilibrium model. It builds on the assumptions that the slope consists of rigid materials and that possible ruptures occur along a single failure plane (the slip surface). The shear stress acting on the slip surface is compared with the shear strength of the materials resisting along the slip surface. The fraction of the contrasting forces acting on the failure plane is expressed by the factor of safety *FS* (Carson and Kirkby, 1972; Crozier, 1986; Duncan and Wright, 2005). In the case of an infinite slope model this is simply the dimensionless ratio between the resisting (stabilizing) force *R* and the driving (destabilizing) force *T* (Fig. 1A),

$$FS_{\mathrm{I}} = \frac{R}{T}, \tag{1}$$

where FS_{I} is the *FS* based on an infinite slope model. For more complex geometries, *FS* is the ratio between the sum of resisting forces or moments and the sum of driving forces or moments. When $FS > 1$, $R > T$, and the slope is considered stable. $FS = 1$ indicates the meta-stable condition produced by the equivalence of *R* and *T*. When this occurs, the slope is considered to be at the point of failure. $FS < 1$ or $R < T$ corresponds to unrealistic physical conditions, and are taken as an indication of the instability of the slope under the modelling conditions.

Limit equilibrium models have often been applied to two-dimensional cross sections drawn along the steepest terrain gradient (Duncan and Wright, 2005). The zone above a known, inferred or hypothetical failure plane is partitioned into vertical slices of equal or different sizes. *R* and *T* are computed for each slice (Fig. 1B shows an example for a circular slip surface), and summed up linearly in order to obtain a value of *FS* for the entire slope. Most commonly, the forces acting between the slices are neglected (Fellenius, 1927). In many cases, the simplification leads to a lower value of *FS* (Kolymbas, 2007). Fellenius (1927), Bishop (1954), Janbu et al. (1956), and Morgenstern and Price (1967) have proposed different schemes to calculate *FS* along pre-defined slope profiles and associated failure planes.

When two-dimensional cross sections are used, the width of the potential slope failure and the three-dimensional topography of the slope are not considered. In order to overcome this limitation, the limit equilibrium model was extended, and applied to three-dimensional topographies and associated three-dimensional failure planes (e.g., Hovland, 1977; Hungr, 1987; Hungr et al., 1989). In order to accomplish the calculation of the three-dimensional balance of *R* and *T*, specific software has been designed that can be used to test multiple failure planes, searching for the lowest *FS* value, e.g. CLARA (Hungr, 1988), TSLOPE3 (Pyke, 1991), and 3D-SLOPE (Lam and Fredlund, 1993). A limitation of these computer codes is that they were designed to model individual slopes, or portions of a slope, and cannot be used effectively to model a large number of slopes in an area. Thus, the codes are not suited for a regional analysis of the slope stability conditions.

In the infinite slope stability model, the assumptions are made that the slope is planar and of infinite length, and that the failure plane is parallel to the topographic surface (Fig. 1A). The assumptions simplify the model considerably, and facilitate the application of the model in a raster based GIS, allowing for the application of the infinite slope stability model for regional slope stability analyses. In a raster GIS, the

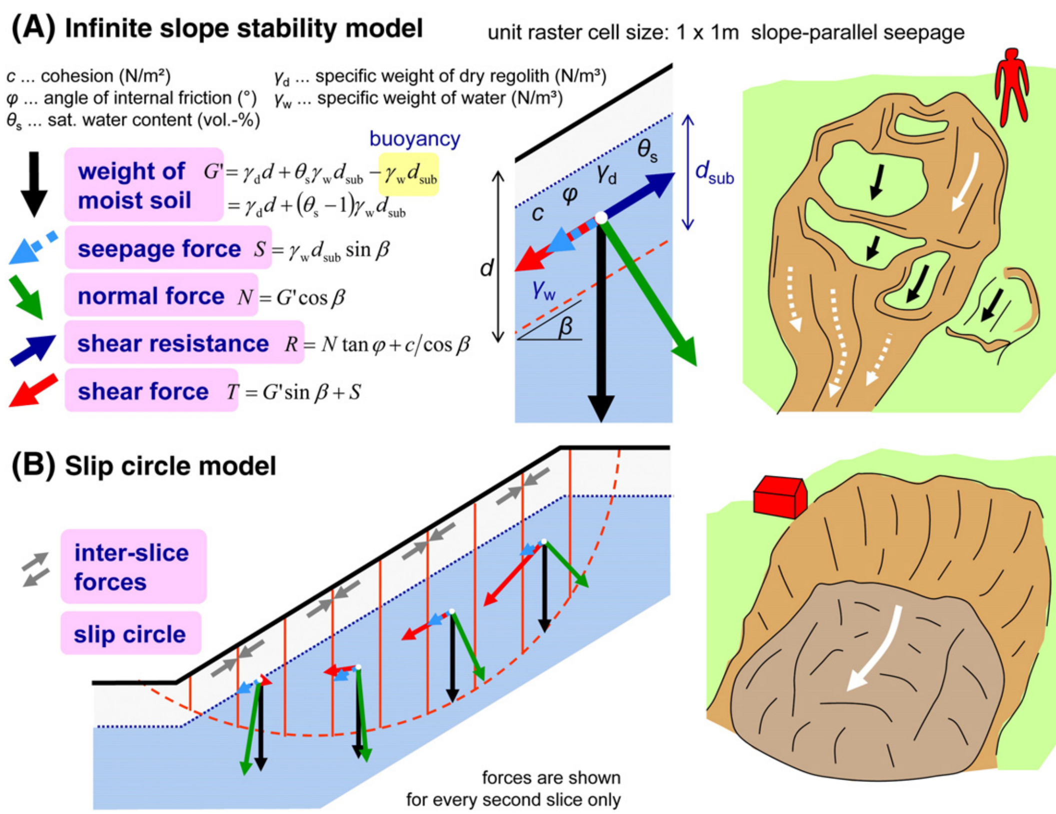

Fig. 1. Slope stability models. (A) Infinite slope stability model. (B) Slope stability model based on a circular slip surface.

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