Runout Modelling of Shallow Landslides Over Large Areas with SliDepot

Daniel Tobler, Rachel Riner, and Robert Pfeifer

Abstract

The GIS-based model SliDepot simulates the runout zones of landslide prone areas. It was developed by GEOTEST AG and applied during the last 10 years for numerous projects. In combination with the SliDisp+ software (modelling of slope instabilities, cf. Tobler and Krummenacher (Modellierung von Anrissgebieten für flachgründige Rutschungen und Hangmuren. In: Proceedings of the 2nd Swiss geoscience meeting, Lausanne, 2004); Tobler et al. (Modeling potential shallow landslides over large areas with SliDisp+. In: Proceedings of the second World landslide forum, Rome, 2011) SliDepot allows to calculate decisive parameters for the dimensioning and optimized positioning of protection measures.

In contrast to other GIS-based models "Casadei et al. (Earth Surf Process Landf 28:925–950, 2003); Godt et al. (Eng Geol 102(3–4):214–226, 2008)", SliDepot does not rely on a single-flow approach, which calculates the flow direction by direct neighbourhood relationship. The software is capable of analysing multiple cells in a 20°-sector above a potential runout area up to the extent of four cells. The potential runout cell will only be connected to the runout area if the mentioned 20°-sector contains an instable cell or if the necessary initial volumes of mobilised mass are guaranteed. Furthermore the program also considers geomorphologic phenomena like convex topography. With this approach the runout direction is simulated fairly realistic.

The runout is based on the degradational water content of the sliding mass during its downslope movement which finally leads to the break-off. Results from a case study in Switzerland will be presented.

Keywords

Shallow landslide modelling • Runout modelling • Protection measures • Case study • SliDepot model

Introduction

In mountain regions many residential areas as well as important lifelines are generally exposed to potential shallow landslide events. Spatial planning is one of the major key elements in protection against natural hazards and requires a comprehensive assessment of landslide processes (Glade et al 2005; Sidle and Ochiai 2006). By applying process models, the extent of potential landslides can be calculated over large areas (Guzzetti et al. 2006; Zolfaghari and Heath 2008).

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The resulting maps provide a quick identification of endangered areas with conflicts between hazards and land use. It is the base to set priorities for a more accurate hazard assessment. Moreover, due to the importance of cost efficiency the planning of protection measures calls for (more) detailed information about the intensity and probability of expected landslide incidents for a given area. The model SliDepot calculates the runout of shallow landslides (the distance downslope that the shallow landslide will affect).

Travel distance of a debris flow once it reaches a low-gradient surface is a function of its volume and viscosity (Wakatsuki and Matsukura 2008; DeRose 1996). The solid volume of a debris slide or flow deposit is a function of soil depth, distance traveled down the hillslope, and the gradient of the traveled path. The proportion of water is the main control on viscosity. Several studies have suggested a relationship between runout distance and the angle of internal friction of shallow landslides (Corominas 1996; Griffiths et al. 2002). Others predict a simple volumina-depending relationship of the maximal runout distance. Hayashi and Self (1992) or Legros (2002) for example postulate:

$$L_{max} = 15.6V^{0.36}, \tag{1}$$

where L_{max} is runout distance and V is the volume of the landslide. Clearly this relationship is sufficiently strong to form the basis of a runout distance calculation, but it requires that a landslide volume be derived. This is problematic as it requires a calculation of both the surface area of the landslide and its depth, neither of which are easy. Intensive field investigations are necessary to determine the required parameters (Salciarini et al. 2006).

The model SliDepot calculates runout distances of shallow landslides within a given area efficient and fairly realistic. The above mentioned relationships between runout distance and volume, viscosity of the subsoil, roughness of subsoil, vegetation and slope gradient are summarized in an empirical parameter. With this simplification an implementation of the complex thematic in a GIS is possible – modeling of runout distances from potential landslide detachment zone of large investigation areas are easy to handle.

Shallow Landslide Modeling

General Remarks

The process of shallow landslides has to be divided into two sub processes – the detachment- and the runout process (Lourenco et al. 2006; Rickli 2001). Both processes can be modeled with different approaches.

Detachment (Source) Zones: Model SliDisp+

SliDisp is a deterministic numerical model which calculates the landslide susceptibility of slopes (Liener et al. 1996). The original model was developed by Liener (2000) at the University of Bern. Studies in several test areas showed that the assessment of detachment zones for potential shallow landslides must inevitably take pedological aspects as well as joint water-input from the underlying bedrock into account (Guimarães et al. 2003; Rickli and Bucher 2003; Dahal 2008). During the last 5 years different alterations were carried out and the program advanced to SliDisp+ (Riner 2009).

The model SliDisp+ determines the stability of the slope for each cell within the grid by applying the Infinite-Slope-Analysis, using the simplified safety factor F (Selby 1993, see Fig. 1). F will be calculated to describe the ratio of retentive and impulsive forces. Fundamental basic data are the slope angle, derived from the DEM (cf. Legorreta Paulin and Bursik 2009) from which the thickness of soil will be deduced and the geology which allows to determine friction angle and cohesion (VSS 1998) as geotechnical parameters (Meisina and Scarabelli 2007). To consider the high natural variability of the sheering parameters these values are not described as single values per geological class but as normal distribution, calculated with randomly chosen values.

For the model calculation a term for root cohesion (WK) has been added the original formula of the factor of savety F. This empirical adjusted parameter takes the roots retaining forces of vegetation layer into account (Schmidt et al. 2001; Chok et al. 2004; Hales et al. 2009; see formula [2]).

$$F = \frac{WK + c' + (\gamma \cdot z \cdot \cos^2\beta - \gamma_w \cdot m \cdot z \cdot \cos^2\beta) \cdot \tan\varphi'}{\gamma \cdot z \cdot \sin\beta \cdot \cos\beta} \tag{2}$$

WK: Root cohesion [kN/m^2]
c′: cohesion [kN/m^2]
γ: specific bulk density [kN/m^2]
z: soil thickness [m]
β: slope angle [°]
γ_w: specific bulk density of the saturated zone [kN/m^2]
m* z: height of the water table [m]
φ: friction angle [°]

The safety factor F is calculated for each cell of the grid, based on the data from the digital elevation model (DEM). If F < 1, the cell is potentially instable, and the material can be set into motion by triggering factors. The total of all instable grid elements equals the maximum detachment area (= landslide susceptibility).

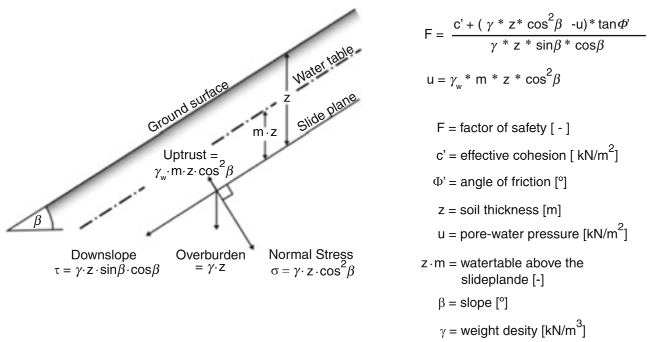

Fig. 1 Principle for the calculation of the factor of safety F for every raster cell (Selby 1993). Indication of all parameters needed for the calculation, except the root cohesion (WK, see formula [2])

The normal variation of shearing parameters is acknowledged by a Monte-Carlo-Simulation. By applying this method, 100 random values are chosen from the deviation of the shearing parameters to calculate the factor of safety (F). With this random combination of parameters, the factor of safety is calculated 100 times for each cell. We assume that both – the cohesion and the friction angle – show a normal distribution and do not correlate with each other (Lacasse and Nadim 1996).

Areas with more than 60 % of the parameter combination showing a safety factor $F < 1$ are indicated as potential sources. If there are more than 90 % of the F-values <1, a medium to large chance of a potential landslide is expected. The data preparation as well as its visualisation is carried out by means of a geographic information system (Liu and Wu 2008). The calculation of the stability factors is implemented by a C-application and then integrated in to the GIS.

If there are only fragmentary or rough digital input data available (geology, underground data) the model output will be insufficient. In that case the source zones should be defined from a simple slop-analysis. The slop-analysis should be based on the nationwide available event statistic (AGN 2004) for a certain underground. For such cases it is recommended to let field experts map the detachment zones. On that base the run out zones of shallow landslides can be calculated with SliDepot.

The quality of the results correlates directly with the quality of the input parameters in SliDisp+. The better the knowledge of the underground, the hydrogeological system and the soil cover, the better the results for the detachment zones will be.

Runout: Model SliDepot

SliDepot is an absolute GIS modeling. Starting with the data from the defined source zones the distribution of material in downhill flow direction is calculated. The model focuses on the amount of water within the shallow landslide that will be reduced during the natural process. Finally the lack of process water will determine the point where the distribution of material stops. In contrary to many other GIS applications for runout calculations (Lineback Gritzner et al. 2001; Zolfaghari and Heath 2008), the model does not use a “single-flow” approach to calculate the flow direction. This model bases on a complicate, advanced nearest neighbor analysis.

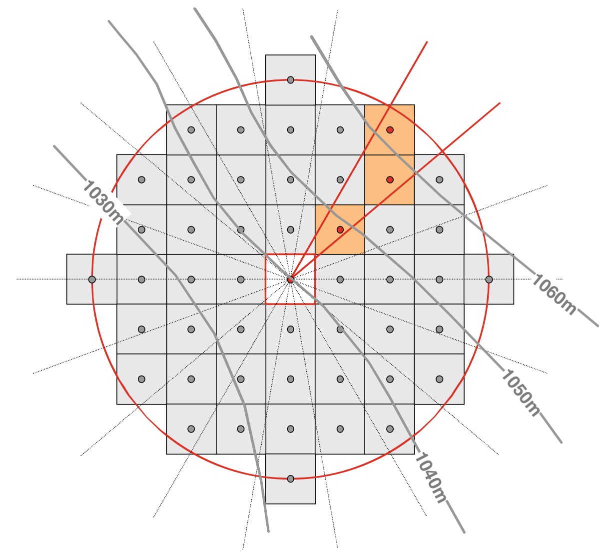

Fig. 2 Three analyzed grid cells of the sector for cell exposition from 210° to 230° (example: 5 m cell → radius of *red circle* = 20 m)

For the modeling, the runout movement of a shallow landslide has to be divided in two different parts: the calculation of the flow direction and the calculation of the maximal flow distance. For the flow direction, several cells within a 20°-section above (inverse direction to the cell exposition) a potential distribution cell and up to an extension of four grid cells are analyzed (Fig. 2). For the focused grid cell the distribution will be calculated if (a) there is a detachment cell respectively a cell with sufficient water saturation and (b) when the topography of the section is strongly convex. The SliDepot approach allows a far better prediction of the distribution direction than the ‘single-flow’ approach.

For the calculation of the maximal runout distance the water content of the sliding mass is the most important parameter (Hölting and Enke 1996). With every distribution step the neighboring cells up to a distance of 20 m (for grid cells of 5 × 5 m) will be analyzed. By using a local reduction parameter the quantity of starting water (i.e. 1.0) respectively the remaining actual amount of water is reduced. This parameter is mostly determined by the local slope gradient, the type of underground as well as the vegetation (e.g. forest). The term underground summarizes the soil type, the terrain roughness and the topography itself. The availability of accurate data finally determines the reducing parameters. Hungr (1995) as well as Hancox and Wright

Table 1 Possible reduction factors for the runout calculations with SliDepot. Note influence of slope gradient and vegetation (grassland, forest, cf. Hancox and Wright 2005)

Slope gradient	Reduction parameters according to distribution step number (Maximal runout distance)				
g: grass		1	2	3	4
f: forest	Original starting value	(20 m)	(40 m)	(60 m)	(120 m)
>25° (g)	1.0	0.85	0.72	0.61	...
>25° (f)	1.0	0.60	0.36	0.22	
17–25° (g)	1.0	0.75	0.56	0.42	...
17–25° (f)	1.0	0.50	0.25	0.13	
10–17° (g)	1.0	0.65	0.42	0.27	
10–17° (f)	1.0	0.40	0.16		
<10°(g)	1.0	0.45	0.20		
<10° (f)	1.0	0.20			

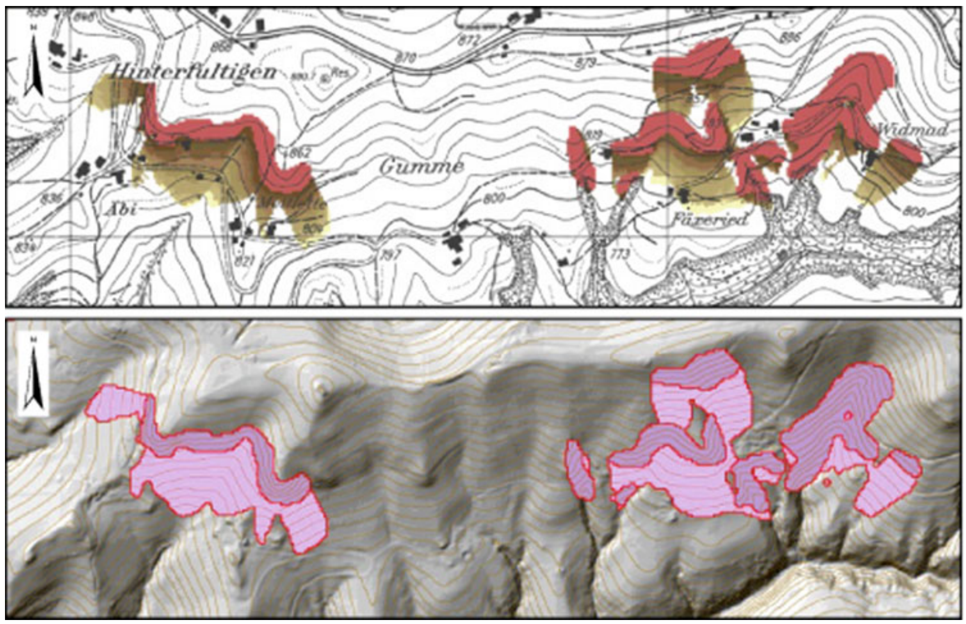

Fig. 3 Calculated source and runout zones of possible shallow landslides in the Bernese Prealps (Switzerland); *reddish-brown* = detachment zone; *brown* = calculated runout with SliDepot (*above*). Generalized view for the presentation on the hazard maps; *dark Lila*: detachment zone; *light lila*: runout zone

(2005) describe a possible way of the implementation of a reduction parameter. The distribution stops if either a pre-defined number of distribution steps (i.e. 8) achieved or if the calculated water amount drops below a pre-defined threshold (i.e. 0.1). As an example Table 1 shows a typical reducing parameter and the maximum range of a hypothetical distribution under stable conditions (slope angle, forest).

With the above mentioned parameters the average angle of reach lies between 25° and 30° in grassland areas. In the forest the average angle is around 20°. These values correlate with the AGN recommendations (2004) as well as the investigation of Dai and Lee (2002).

Combined Results SliDisp+ and SliDepot

Figure 3 shows the results of a runout calculation from shallow landslides. Starting at the dark red areas (calculated source locations for shallow landslides with SliDisp+, cf. Tobler and Krummenacher 2004; Tobler et al. 2011) the run out zones are calculated. The starting amount of water is reduced within eight steps each of 20 m. Usually the final number of necessary discharge steps and therefore the maximal distribution range is calibrated with the event register or silent witnesses.

Case Study, Lauterbrunnen, Switzerland

Investigation Area

In 2010 model calculations with SliDisp+/SliDepot (runout) have been carried out within the settlements (approx. 30 km^2) of the community of Lauterbrunnen during a review of the existing hazard map (GEOTEST AG 2003).

Fig. 4 Investigation area for the review of the hazard map in Lauterbrunnen, central Switzerland (Swissmap 2011)

Fig. 5 View from the South through the Lauterbrunnen valley with the steep cliffs of limestone and landslide susceptible deposits in the valley bottom

Lauterbrunnen is situated in central Switzerland at an altitude of 800–1,500 m a.s.l (Fig. 4). The bedrock consists mainly of schist and sandstones of the Aalenien and the Bajocien (Dogger), sandstones of the Oxfordien and Callovien, as well as compact Malm lime and sediments from the Tertiary (Günzler-Seiffert 1962). The rock is folded in a large scale and disrupted by several steep tectonically displacements. The weathering resistant lime and the sandstones form striking steep rock walls falling towards the valley bottom (Fig. 5). The schists of the Aalenien are very susceptible to landslides (GEOTEST AG 2007)

On both sides of the valley the rock is covered by silty moraines, dislocated slope debris and historic deposit from rock falls. The bottom of the valley consists of fine-grained flood sedimentation from the river and shows a heterogeneous layering of material.

Results

Figure 6 shows the source areas (detachment zones of shallow landslides in red) calculated with SliDisp+ as well as the runout areas (brown-yellow) calculated with SliDepot (GEOTEST AG 2011). Starting from the dark red areas (calculated source locations for shallow landslides) the runout areas are modeled by stepwise reducing the original water content through max. eight discharge steps, each of 20 m. For Lauterbrunnen an excellent event register exists. So the final number of necessary discharge steps and therefore the maximal runout range has been calibrated with silent witnesses from events in 1999 and the event register (GEOTEST AG 2007). The average angle of reach of all shallow landslides is 27° and lies within the range postulated by Dai and Lee (2002).

The model results (SliDisp+ and SliDepot) indicate the landslide prone areas within the investigation perimeter. For creating a hazard map process intensities have to be added to the susceptibility map. Therefore additional field investigations focused (a) on the verification of modeled areas and (b) on the definition of the process intensities. AGN (2004) defines the different process intensities in hazard mapping. The actual hazard map is shown in Fig. 7. Comparing the calculated areas (Fig. 6) with the hazard map it is obvious, that nearly all hazard zones have a smaller extension than the modeled process areas. The model results suit for hazard indication map, but still not for hazard maps.

Conclusion

There are a lot of uncertainties not considered in the study of calculating the runout areas. These uncertainties underlying the model may include the type of material, mechanism of failure, groundwater, the volume of failure and the geology. The parameters obtained are applicable to predict the travel distance on regional scales, and provide an effective means for the assessment of runout distance of landslide mass when incorporated into a map showing slope instability and the digital elevation model (DEM) within GIS.

With a sophisticated GIS approach it is possible to produce innovative runout maps. The comparison with silent witnesses and the event register indicate that the model is useful and suitable for the scale adopted in this study (hazard indication map) For a hazard map additional field investigations have to be done.

With SliDepot it is possible to calculate and indicate slopes with a higher disposition for shallow landslides over large-scale areas (several km^2). The calculation helps to identify conflict zones between damage potentials and process areas, which again enables efficient spatial

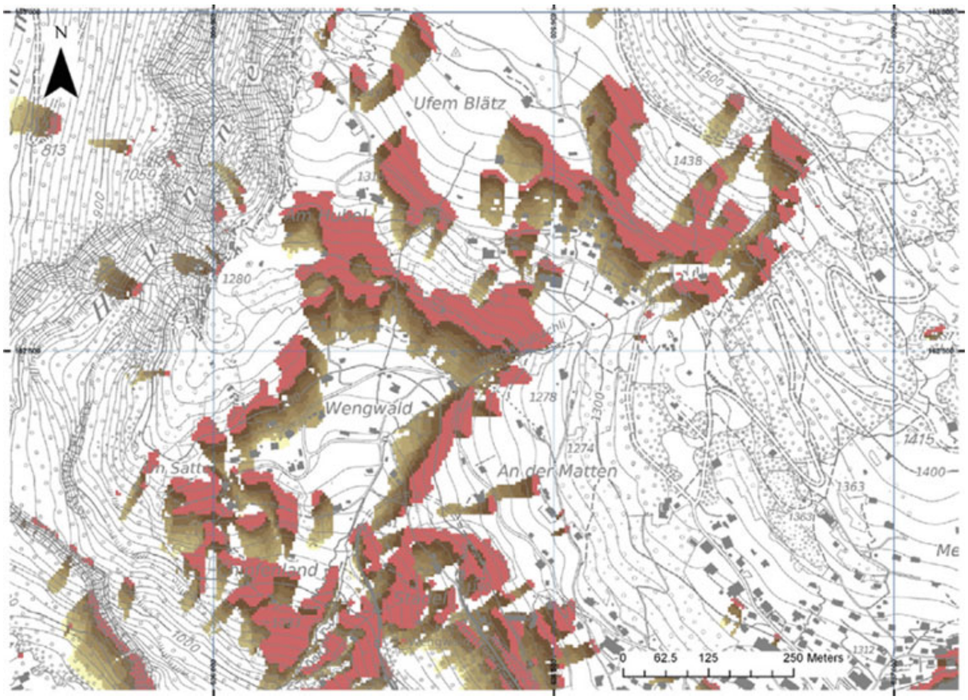

Fig. 6 Section of the calculated shallow landslide areas in Lauterbrunnen (*red* = source modeled with SliDisp+; *brown-yellow* = runout modeled with SliDepot)

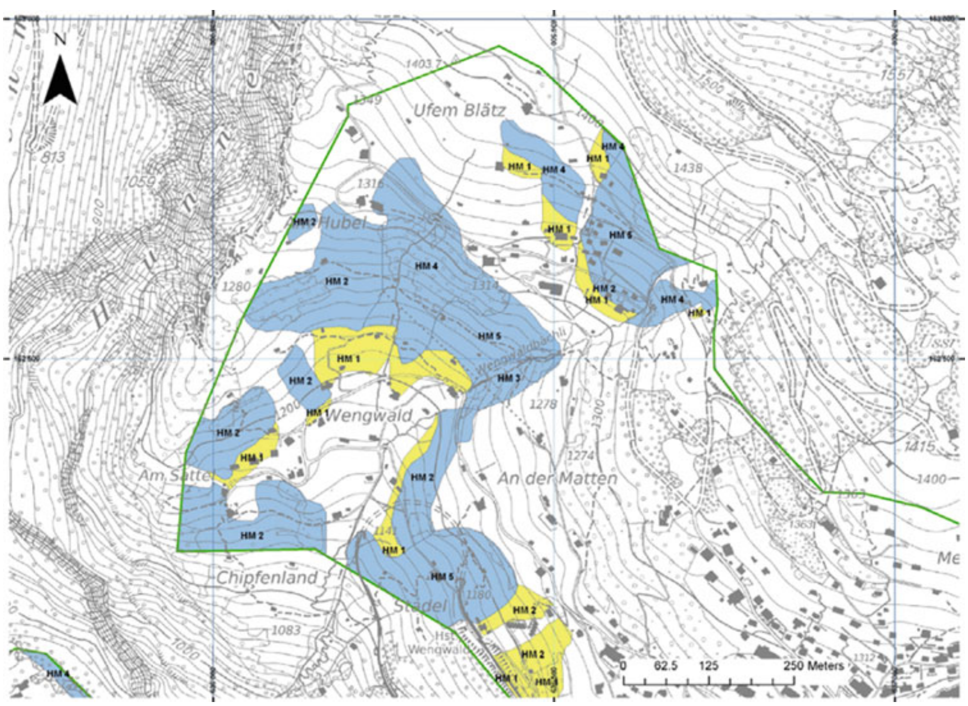

Fig. 7 Section of the actual hazard map for shallow landslide processes of Lauterbrunnen with hazard levels (*blue* and *yellow areas*; *green* = investigation area, GEOTEST AG 2011). The *numbers* indicate the field in the intensity-probabilty diagram (AGN 2004)

planning or the definition of measurements to protect human lives and the infrastructures.

In future it will be a challenge to implement water content of the sliding mass and detailed underground conditions into the reduction parameter of the runout model. At the actual state the model SliDepot may be used for hazard indication maps. With additional field investigation hazard map quality will be achieved.

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