Preliminary results of slope stability simulations for the prediction of debris flows in the Central Andes (Mendoza, Argentina)

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Abstract. The preliminary results of debris flow simulations for some selected study areas along the international road corridor Mendoza (Argentina) – Valparaíso (Chile) are presented at the example of one small catchment. A deterministic coupled hydrological-slope stability model based on Open Source GIS products was designed for predicting the response of selected slopes and small catchments to rainfall events, including failures due to saturation of the soil as well as erosion due to the kinetic energy of overland flow. Samples were taken in the field and analyzed for their physical and mechanical characteristics in a geotechnical laboratory. Hydrological characteristics were derived using pedotransfer functions. The preliminary simulation results were promising, but more research is required for enabling a better evaluation and an optimization of the model.

Keywords. shallow slope failure, debris flow, numerical simulation, Mendoza Valley, Andes.

1. Introduction

Debris flows are rapid mass movements forming a mixture of rock fragments and water. They are intermediate between sediment-rich floods and landslides. Initiating as failures on slopes, in gullies or at gully walls, they are usually driven by seepage forces (saturation of the soil), or by the kinetic energy of overland flow, or by a combination of both. Debris flows are common phenomena in mountain regions all over the world, and they are strongly related to intensive or prolonged rainfall, often in association with intense snowmelt. As they often constitute a significant hazard for buildings and infrastructures, and therefore also for human lives, several qualitative, statistical and deterministic approaches have been developed in order to predict the occurrence of debris flows in space and time. However, up to now many models exist for modelling specific processes being involved into the initiation and movement of debris flows, but few approaches are known to simulate the entire process from rainfall impact to final accumulation. The model presented in this paper attempts to fill this gap. The hydrological modules and the identification of unstable cells are based on the Open Source GIS Software GRASS. With the identified regions of potential failure and starting mass, the motion and run-out of the debris flow should be calculated with a dynamic model. Such a model can be based e.g. on the Savage-Hutter model (SAVAGE & HUTTER 1989; PUDASAINI & HUTTER 2007). This final step, however, has not yet been implemented at the present stage of the project.

2. Study area

The research project includes selected study areas along the international road corridor from Mendoza/Argentina to Valparaíso/Chile between Potrerillos and Los Andes (Mendoza and Aconcagua valleys, Fig. 1), where some qualitative (MIKKAN 1997) and statistical studies on debris flows (MOREIRAS 2004, 2005a and b) already exist. The study areas are seven small catchments (few km²) susceptible to debris flows and with a meteorological station in their vicinity. The paper discusses the first results for the study area Guido A (Fig. 1), located about 50 km W of the city of Mendoza, between 1500 and 2750 m asl., covering 2.0 km². It constitutes a well-defined and rather homogeneous catchment, with granite outcrops and partly relocated residuals from weathering. Mean annual precipitation at the Guido Meteorological Station (5 km away) was 202 mm in the period 1970-2000. Excluding steep rocky slopes the catchment is covered in *Monte* shrubland, dominated by certain species of *Larrea* and further drought-resistant shrubs.

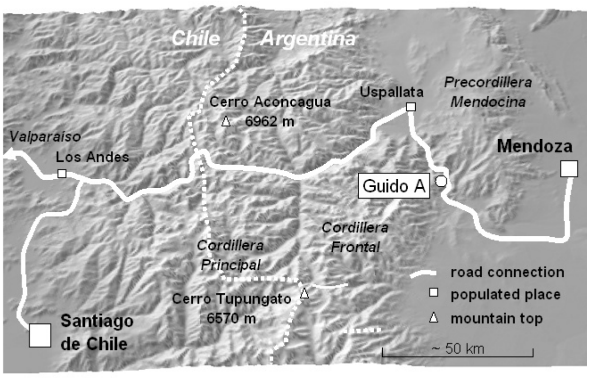

Fig. 1: The international road corridor Mendoza – Central Chile and the study area Guido A (left, hillshade from SRTM data); view of the study area Guido A from the opposite slope (right,, photo by M. Mergili). Note the international road crossing the distal part of the fan. The bottom of the photo represents a width of about 600 m.

Certain debris flows disrupting the international transit have been reported for the Guido area by the road maintenance agency, like during the afternoon and the evening of 08.04.1996 (later referred to as Event 1): A daily precipitation of 9.2 mm was recorded at the Guido meteorological station in the morning of the following day. 15,000 m³ of material had to be removed from the road over a total length of 4 km (including Guido A) in order to re-establish traffic. On 21.04.1996 (referred to as Event 2) the international traffic was disturbed by mass movements again. 40.0 mm daily precipitation were recorded at the Guido station, and 600 m³ of material had to be removed in several places at a length of 12 km, not directly including Guido A, according to the reports. This rather astonishing precipitation – disturbance relationship was possibly be caused either by removal of unstable material during the first event, or by local rainfall conditions different to those recorded at the gauge.

3. Materials and Methods

Soil samples were collected and analyzed for their physical and mechanical characteristics. Besides textural features and bulk density, cohesion c and angle of internal friction φ were determined in a laboratory using triaxial tests (Table 1). The major geomorphological and land cover classes in the study areas were mapped in the field and from orthophotos. A high resolution (5 m) digital elevation model (DEM) was derived from stereo pairs of aerial and terrestrial images. Meteorological records from stations close to the study areas were acquired on a daily basis from the Red Hidrológica Nacional (Argentina). Daily precipitation was broken down to short events of high intensity typical for the region. Finally, historical information on debris flow events in the previous years and decades was collected from existing records, newspapers, and official reports (Chapter 2).

Each land cover class was converted into an interception capacity (e.g. according to data published by BRAUD *et al.* 2001). Soil characteristics were assigned to each substrate class using the laboratory results. Hydrological parameters (Manning’s roughness n and the Van Genuchten parameters) were extracted from the sediment characteristics using a pedotransfer table (MAURER 1997, Table 1).

Table 1: The major geotechnical and hydraulic characteristics of the granite residuals covering the study area Guido A as used in the model. ρ_d is dried bulk density, c is cohesion, φ is angle of internal friction, θ_s is saturation water content, and k_f is hydraulic conductivity. Lower threshold values for c and φ are the lowest values in the dataset for the granitic residuals of the Guido area, average values are the arithmetic mean within the same dataset (outliers excluded).

	grain size cl.	ρ_d (kg m^{-3})	c (N m^{-2})	φ (degree)	θ_s (vol-%)	k_f (cm h^{-1})
lower threshold	S (Sand)	1850	0	40.0	43	29.7
average	S (Sand)	1850	2000	41.5	43	29.7

A physically-based model combining hydrological processes and stability criteria was designed to distinguish between critical and non-critical constellations. Slope failures were considered to be initiated by seepage forces (saturation of the soil). Additionally, erosion by the kinetic energy of overland flow was computed. The slopes under investigation were considered as four-layered systems with vegetation, surface water table, soil, and bedrock. The model was implemented into the GRASS GIS environment as a raster module, using the C language.
The following simplifications were required for overcoming the complexity of nature and limitations with the input data: (1) soil was considered homogeneous over its entire vertical extent, without any stratification; (2) bedrock was considered impermeable and unconditionally stable; and (3) surface runoff was treated as unconcentrated overland flow without a predefined stream network.
The required parameters were fed into the model as raster maps, the meteorological data as text files. The model operates in four major steps. The steps (3) and (4) are based on a 3-dimensional matrix required to account for vertical variations of soil water status and failure conditions.

(1) Water input from precipitation is split up between vegetation and soil surface according to interception capacity. Surface water partly contributes to overland flow, and partly infiltrates into the soil. Infiltration is computed analogous to soil water movement (compare below), assuming a saturated top layer of the maximum grain size in the presence of a sufficient surface water table.

(2) Overland flow is simulated using the empirical Manning equation. The length of the time steps is dynamically determined depending upon flow velocity. Surface water table is updated for each pixel.

(3) Water flow between the cells of the soil is computed using the Richards equation for piston flow. Preferential flow is considered to occur only in the skeleton fraction of the soil, using relationships published by SUKHIJA *et al.* (2003). Water content, hydraulic conductivity, matric potential, and pressure head are updated for each time step.

(4) The dimensionless factor of safety *FS*, expressing the ratio between stabilizing and instabilizing forces, is the most widely used approach for is computed for modelling shallow slope failues. It can be expressed in certain ways, the following was chosen and applied to each cell (compare Fig. 2):

$$FS = \frac{1}{L}\left(\frac{c}{\gamma_w d \sin\alpha} + \frac{(L-m)\tan\varphi}{\tan\alpha}\right) \quad \text{Equation (1),}$$

where c (N m^{-2}) is soil cohesion, γ_w is the weight density of water (9810 N m^{-3}), d (m) is soil depth above the considered cell perpendicular to the soil surface, α is the local slope angle, m is the ratio of saturated soil depth to total soil depth (both above the considered cell), and φ is the angle of internal friction. The dimensionless factor L is computed as follows:

$$L = m\frac{\gamma_{sat}}{\gamma_w} + (1-m)\frac{\gamma_m}{\gamma_w} + \frac{R}{d}$$ Equation (2),

γ_{sat} (N m^{-3}) is the weight density of saturated soil, γ_m (N m^{-3}) the weight density of soil at field moisture content, and R (m) is the hydraulic radius. A detailed description of the approach and further literature are provided e.g. by BURTON & BATHURST (1998). Cells with FS > 1 are considered stable, cells with FS < 1 are considered locally unstable. Strictly spoken FS < 1 predicts that an infinite slope will fail. In a first step it is assumed here that each cell will fail separately under such conditions, i.e. the volume of the cell down to the potential failure plane contributes to the total failed volume.

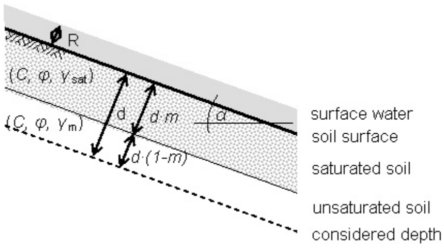

Fig. 2: Variables and arrangement of system elements for the computation of the factor of safety. In most cases the depth of the potential failure plane d is equal to the depth of saturated soil. For abbreviations refer to the text.

Erosion due to the kinetic energy of overland flow is less accessible to fully deterministic methods. Statistical relationships between stream power ω (kg s^{-3}) and detachment rate have been established for some soil texture classes. Stream power is computed as follows:

$$\omega = \gamma_w R v^2 \tan\alpha$$ Equation (3),

where R (m) is surface water table, and v (m s^{-1}) is flow velocity. The detachment rate (m s^{-1}) for sandy soil, as prevailing in the study area, was approached by combining relationships published by ZHANG *et al.* (2003) and SALLES *et al.* (2001).

4. Results

The model was discretized with a horizontal resolution of 10 m and a vertical resolution of 25 cm. Two scenarios were computed, (1) for lower threshold strength parameter conditions, and (2) for average strength parameter conditions (Table 1). Fig. 3 illustrates the temporal variations of failed and eroded volume, flow velocity, and precipitation for the lower threshold strength parameter conditions. Slope failures peak as soon as the first layer becomes saturated, the second peak is connected to saturation of the second layer. About 60,000 m³ failed and 9,000 m³ eroded volume were predicted for Event 2. Erosion occurred mainly in the steeper sections of the valley bottom. Experiments with finer vertical resolutions indicated earlier onset of slope failures and smoother graphs, whereas the total failed volume only changed slightly. For average strength parameter conditions, no slope failures were predicted and erosion by overland flow became the dominant process.

Event 1, at lower threshold strength parameter conditions, led to a total failed volume of about 2,800 m³ according to the model. 300 m³ were simulated to be eroded by overland flow. At average strength parameter conditions, the model predicted no slope failures.

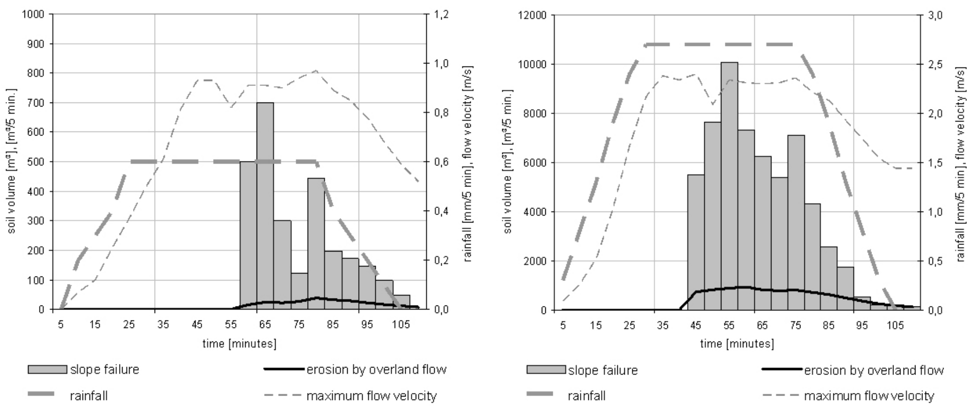

Fig. 3: Temporal development of failed and eroded volumes during Event 1 (left) and Event 2 (right), with precipitation and flow velocity as orientation, for lower threshold strength parameter conditions. Note the different scales of the ordinates.

The spatial distributions of failure depths for the two events at lower threshold strength parameter conditions are shown in Fig. 4.

5. Discussion

The model results for Event 1 show only some few unstable cells on steep, wet slopes. Thus the meteorological conditions were close to the threshold conditions for the potential initiation of debris flows. The 9.2 mm are within the range of thresholds for rainfall-triggered mass movements in the corresponding section of the Mendoza valley in general (6.6 to 12.9 mm per day) statistically determined by MOREIRAS (2005b) and therefore it is concluded that the preliminary simulation results are within a realistic magnitude.

As expected, the model reacts extremely sensitive to changes in input *c* and *φ*. Application of the lower threshold strength parameter conditions led to an overestimation of failures, compared to field observations, but is probably more realistic than the application of the average strength parameter conditions. However, more work is required on this issue, as well as on the investigation of global failure conditions (effects of slope geometry), and on the choice of suitable parameters for the simulation of erosion by overland flow.

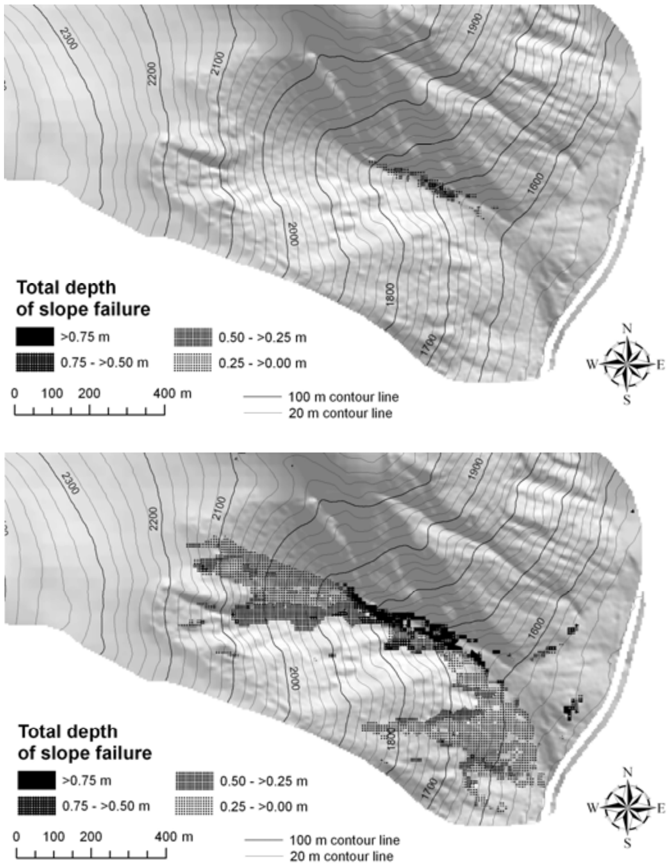

Fig. 4: Modelled potential failed depth during Event 1 (9.2 mm rainfall, top) and Event 2 (40.0 mm rainfall, bottom). The white band at the right repesents the international road.

More validation efforts are certainly required for model evaluation. For all of the areas under investigation, reports of historical debris flow events exist, specifying volumes of material deposited on the road, and being correlateable with certain precipitation (or, in one case, snow melt) events. In order to make the use of this data for validation purposes possible it will be

required to simulate debris flow movement, a complex process. An established model will be used for this purpose (PUDASAINI & HUTTER 2007), and compared to a simple empirical approach.
With the required enhancements and careful validation and parameter sensitivity analysis (soil variables, but also rainfall duration and intensity), the model shall become a valuable tool for the prediction of debris flows on the small catchment scale.

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