FLAC^{3D} and adaptive Kalman-filtering – A new way to install effective alarm systems for landslides?

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ABSTRACT: Numerical approaches are used more often to analyze the stability of rock slopes and valley flanks. This paper illustrates the investigation of the deep-seated rock slide "Steinlehnen" in Northern Tyrol by the continuum mechanics code FLAC^{3D}. As no material parameters from in situ or laboratory tests have been available the determination of the parameters was realized by trial and error methods in the framework of inverse analysis. Adaptive Kalman-filtering techniques allow the estimation of material parameters by comparing the displacements of the calculation with the ones of the tacheometry. Due to the long calculating time at this point the Kalman-filter is used on simple slopes with a small number of grid points. The investigations show that the predictions of strength parameters are possible but still some optimizations are necessary.

1 INTRODUCTION

Mass movements are natural morphological processes in mountain areas. They represent a danger for people as well as for infrastructure and buildings. Because of increasing settlement activities and the simultaneous appearance of extreme climatic conditions the analysis of landslides becomes more and more important. The investigation and installation of alarm systems targets on increasing safety and restriction of human, economical and environmental damage.

In the last several years analysis of such natural phenomenons are more often done by numerical models (e.g. FLAC^{3D}). The objectives of this study are the combination of monitoring data (tacheometer measurements) with a numerical model which represents the failure mechanism of the slope. Finally the model should allow the prediction of future critical states of the slope. It will be one central component of a new type of data- and knowledge-based alarm system.

In the framework of the project KASIP (=Knowledge-Based Alarm System with Identified Deformation Predictor) a new calibration-method for numerical methods should be investigated (Schmalz et al. 2010). Usually the determination of the generally non-homogeneous and non-isotropic material-parameters (friction angle, cohesion, bulk and shear modulus etc.) is realized by geotechnical lab analysis or trial and error methods in the framework of inverse analysis. For future model calibrations it is planned to use adaptive Kalman-filtering techniques (Gelb et al. 1974, Heunecke 1995, Eichhorn 2005) which upgrade the numerical model and the material parameters by comparing the displacements of the calculation with the ones of the tacheometry.

2 STUDY SITE

The study site investigated "Steinlehnen" is located in Gries im Sellrain in Northern Tyrol (Austria). The endangered zone is situated in the polymetamorphic Ötztal-Stubai crystalline complex of the Austroalpine units. The unstable mass consists of paragneisses, amphibolites and granodiorite-gneisses, which are highly disjointed (Figs 1-2). The lithological contacts dip shallowly into the slope (Zangerl et al. 2007). The slope strikes to east with a slope angle between 30° and 40°. The joints have nearly the same orientation as the slope and a dip angle of 50° (Fig. 2).

The slope instabilities and permanent movements in the area of "Steinlehnen" are a result of debuttressing and stress redistribution after deglaciation. Figure 1 shows the different sliding masses bounded by primary scarps and characterized by different rates of movement (Zangerl et al. 2007). In summer 2003 acceleration of a highly active slab occurred and induced a series of rock fall events, the total deformations reached 25 meters within few months (Fig. 3). Due to the hazard of close homes and the federal road a monitoring system was deemed necessary. Because of intensive rock fall events initially a terrestrial laser scanner was installed.

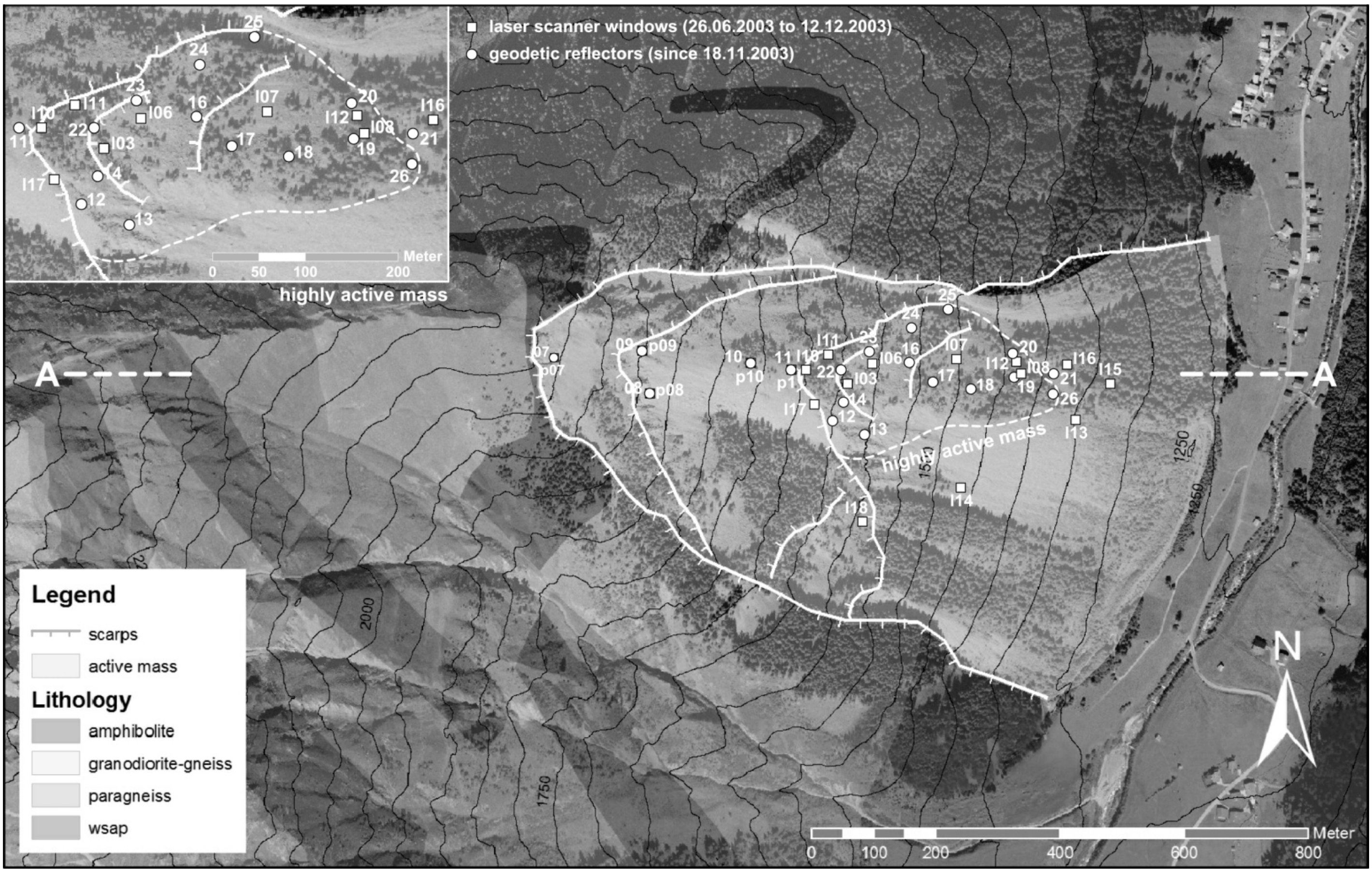

Figure 1. Areal view of the landslide “Steinlehnen” showing the three scarp boundaries, the most active sliding mass and the homogeneous areas with same material parameters. Location of geodetic reflectors and terrestrial laser scanner windows are marked (modified after Zangerl et al. 2007).

Several months later (November 2003) when slope activity decreased surface-mounted reflectors for a total station were installed in the highly active slab. In spring 2004, the slide re-accelerated with deformations of circa 2 meters in half a year followed by a period of re-stabilization down to a movement rate of 25 centimeters per year that remained steady till today (Fig. 3).

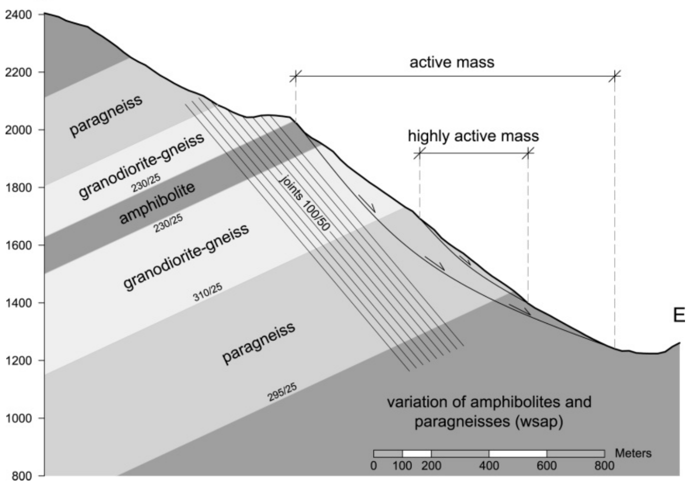

Figure 2. Geological W-E cross section (see Fig. 1 for location A-A) through the landslide “Steinlehnen”.

The displacement vectors for the most active slab show dips of 43° in the upper part and 31° in the lower part. The thickness of this mass is between 10 and 20 meters, the total thickness of the larger deep-seated rockslide system may reach about 70 to 100 meters (Zangerl et al. 2007).

Given that no long-term monitoring data are available it is difficult to assess potential for catastrophic failure. According to historical accounts in the last few hundred years several rock fall events occurred which are a sign for high activity also in the past. The problem is that the trigger that induces acceleration of the sliding mass cannot be resolved. The dip angle of the displacement vectors flattens during progressive slip, this may suggest a reduction of the active driving forces and an increase of the passive resistance forces (Zangerl et al. 2007).

3 NUMERICAL MODELING WITH FLAC^{3D}

3.1 *Modeling procedure*

The numerical modeling is performed by using the continuum mechanics code FLAC^{3D} from Itasca Consulting Group, which bases on the finite difference method (Itasca 2009). FLAC^{3D} perfectly allows the modeling of great deformations and the failure of materials (Stead et al. 2001).

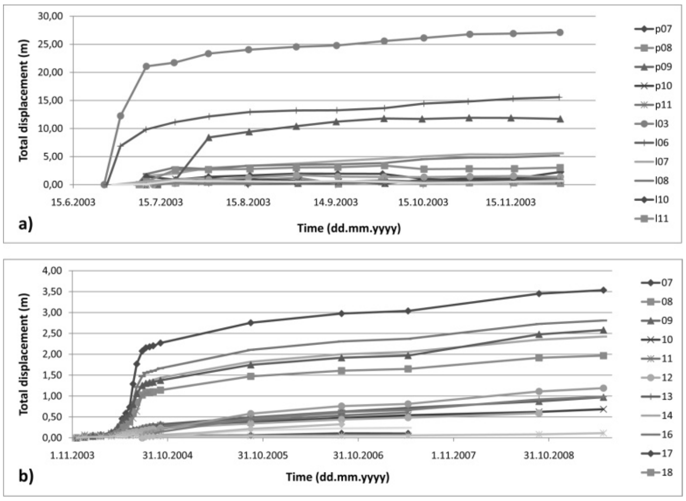

Figure 3. Total displacements obtained from a) laser scanning in the time interval 26.06.2006 to 12.12.2003 b) tacheometer measurements between 18.11.2003 and 29.05.2009.

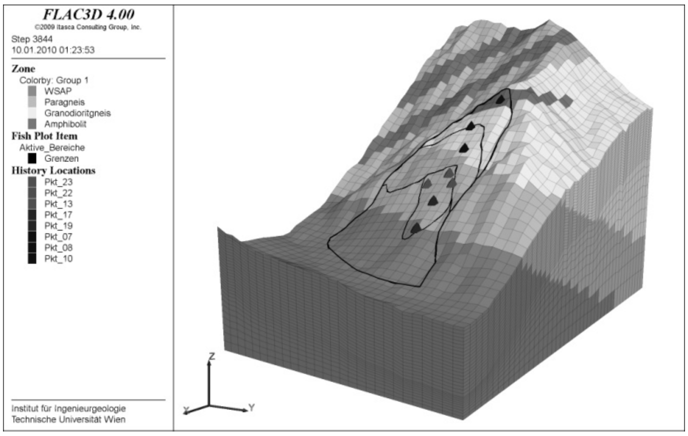

Figure 4. FLAC^{3D} model of the landslide "Steinlehnen" (50 m grid) showing the active sliding masses, the homogeneous areas with same material parameters and the history locations.

The model geometry is based on a digital elevation model (DEM) from airborne laser scanning in the year 2003. The investigated area is 2.2 km long and 1.4 km wide (Fig. 4) and covers an elevation ranging from 1200 to 2400 m a.s.l. (Fig. 2). Given that the solution time increases significantly by increasing the mesh resolution (Preh & Zapletal 2006) three types of meshes with horizontal grid distances of 25, 50 and 100 meters were developed. To reproduce the failure mechanism in an accurate way it is necessary to use fine discretizations for the active areas of the slide. In this case the region of interest (upper layer with uniform zones) was modeled as a layer with a thickness of 300 meters according to the fact that the depth of the failure zone of the rockslide has been estimated with about 100 meters.

The determination of the homogeneous areas with same material parameters results from a geological field mapping (Fig. 1). The data were provided by the project partner alpS GmbH (Innsbruck, Austria).

The behavior of the rock mass is simulated by using a ubiquitous-joint model, which is based on the mohr-coulomb model and allows the implementation of strength anisotropies due to embedded planes of weakness. So it was possible to consider the lower parameters for cohesion and friction angle in the joints. The in situ stresses were calculated on pure elastic material behavior. Plastic deformations were prevented by high strength of the rock. After calculating the in situ stresses, the failure was triggered by variation of strength parameters (Preh & Zapletal 2006).

3.2 *Parameter study and failure mechanism*

The selection of parameters is often the most difficult element in the generation of a model because of the high uncertainly in the parameter database (Itasca 2009).

Geotechnical parameters are conventionally derived from in situ or laboratory tests, but even with those tests the field data will never be known completely. In this study no such data were available so the first set of parameters had to be estimated with the help of literature (Czech & Huber 1990, Tentschert 1996, Kuntner 2006). The ubiquitous-joint model was build up with this parameters and the limited equilibrium was determined by successive reduction of the cohesion and friction angle (strength reduction technique). In a next step the parameters for the limited equilibrium were varied marginally so that the data from numerical modeling match with the monitoring measurements (trial and error method). Therefore displacements, dip directions and dip angles of significant points of the slope surface were recorded. The location of monitoring points corresponds as closely as possible to the location of geodetic reflectors and terrestrial laser scanner windows (Figs 1, 4). Due to the four homogeneous areas it was difficult to determinate the material parameters. The parameters that show the best match with the actual situation are listed in Table 1 and 2.

Table 1. Mechanical properties of rock matrix.

Matrix	amphi-bolite	ortho-gneiss	para-gneiss	wsap *
ρ (kg/m³)	3100	2850	2830	2965
E (GPa)	12.50	16.00	9.25	10.87
ν (-)	0.29	0.29	0.29	0.29
c (MPa)	6.00	3.50	2.60	4.30
φ (°)	55	60	45	50

* variation of amphibolites and paragneisses

Table 2. Mechanical properties of joints (100/50).

Joints 100/50	amphi-bolite	ortho-gneiss	para-gneiss	wsap *
c_j (MPa)	0.40	0.20	0.10	0.30
φ_j (°)	35	37.5	30	32.5

* variation of amphibolites and paragneisses

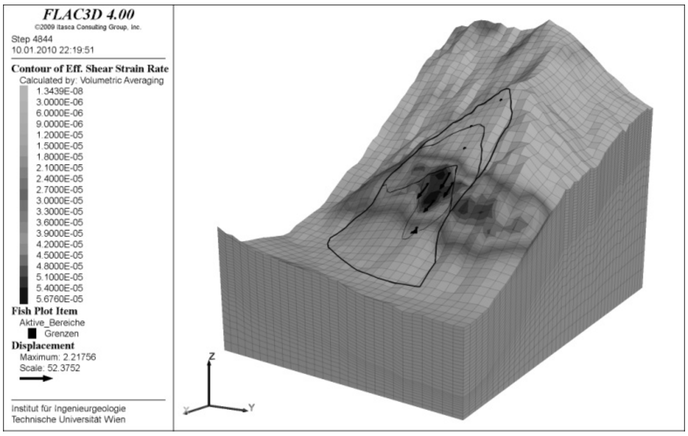

Figure 5. Contour plot of effective shear strain rate and displacement vectors of history locations

The distribution of the shear strain rate is an indicator for the depth and enlargement of the active slide. Figure 5 shows that the shear band (failure zone) corresponds to the location of the highly active slab. The displacements within the failure zone are decreasing continuously with increasing depth which identifies the failure mode "slope creep" (Poisel & Preh 2004). For future analysis it is planned to integrate the effect of water in the numerical model.

4 KALMAN-FILTER AND ALARM SYSTEM

As already mentioned the determination of geological parameters for numerical models is very difficult. Usually it is done by geotechnical lab analysis or trial and error methods in the framework of inverse analysis. By the use adaptive Kalman-filtering techniques it should be possible to estimate and upgrade the numerical model and the material parameters (cohesion and friction angle) by comparing the displacements of the calculation with the ones of the tacheometry.

Due to the long calculating time till now the Kalman-Filter was not used on the model of the landslide "Steinlehnen". Currently the filter is used on a simple slope with 90 grid points and homogeneous material parameters (Schmalz et al. 2010). The investigations show that the predictions of strength parameters for a FLAC^{3D} model are possible but some optimizations in the stochastic model of the Kalman-filter are necessary.

The knowledge-based part should act as a superordinated alarm manager which combines and evaluates the calibration, simulation and/or prediction results of the numerical model with additional hybrid expert knowledge. Those will be measuring results from the monitoring system, additional local deformation models (e.g. polynomials or spectral analysis) and heuristic knowledge from landslide experts.

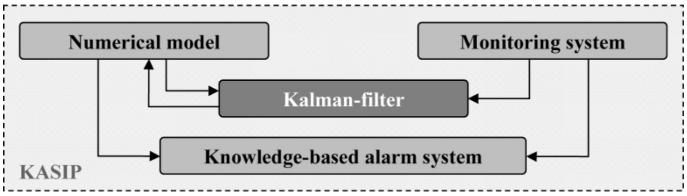

Figure 6. Assembling of the alarm system KASIP

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