Concept of a multi-scale monitoring and evaluation system for landslide disaster prediction



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Abstract

In 2006, OASYS, an EU funded project on a multi-scale monitoring concept for landslides as a basis for an alert system, was completed. 12 institutes from 6 countries tried to merge their multidisciplinary knowledge in the field of landslides and disaster management. The main goal of the research was to develop a cost saving concept for landslide disaster prediction in areas with a higher density of landslides. The present paper reports about the innovative steps and about some highlights of the research, emphasising mainly three tasks:

- GIS integrated geological evaluations of remote-sensing data to delineate the high-risk areas in regions with a larger number of landslides
- geometrical analysis of the monitoring data by fuzzy techniques as a basis for the design of the sensor network and
- geomechanical modelling of the landslide by FD-methods as a basic information for an alarm system.

Kurzfassung

Im Jahr 2006 wurde ein von der EU gefördertes Projekt abgeschlossen, in dem ein mehrstufiges Mess- und Auswertekonzept entwickelt wurde, welches eine Basis für Frühwarnsysteme sein soll. Wissenschaftler von zwölf Instituten aus sechs Ländern kooperierten in interdisziplinären Arbeitsgruppen. Eine besondere Herausforderung war, ein kostensparendes Konzept für Regionen mit einer Vielzahl von Rutschungsgebieten entstehen zu lassen. Dieser Beitrag beschränkt sich auf folgende drei Schwerpunkte:

- GIS integrierte geologische Evaluierung von Fernerkundungsdaten, um die Grenzen der Gefahrenzonen zu kennzeichnen
- geometrische Analyse von Beobachtungsdaten mit einem mehrstufigen Fuzzy-System als Basis für ein kostensparendes Design der Sensor-Netzwerke
- geomechanische Modellierung der Rutschungshänge durch FD-Methoden als Basisinformation für ein Frühwarnsystem

1. Introduction

One main challenge of the research was to develop cost saving solutions which can especially be used in areas with a larger number of landslides. A first proposal of a concept was described in [1].

During the last years, an advanced model was investigated in the project, based on large scale monitoring and evaluation as a first step, regional monitoring as a second step, culminating in a multi-component knowledge-based alert system:

1st step: 'Detection of potential landslides (large scale monitoring and evaluation)'. To get the borders of the moving areas and information about the long-term geodynamical processes a large scale evaluation has to be performed, see Sec. 2, e.g. [2]. This includes e.g. the historical data and remote sensing data, such as aerial photographs, optical and radar images from satellites.

Remote sensing techniques (e.g. In-SAR), differential GPS and tacheometric measurements can be used to obtain additional information about the deformation process, see Fig. 1.

Figure 1: Delineation of risk areas using GPS and total stations.

The measurements are usually performed only three or four times a year, and the results are vector fields describing the displacements and velocities. Based on all displacement information available, an advanced analysis algorithm (see Sec. 3) performs the detection of the so-called taking-off-domains, which are areas where the landslides have their origins, on or below the surface. In these zones, deformation can be detected at an early stage. Additionally, the taking-off-domains can give a first insight into the possible progress of the landslides.

2nd step: **'High precision permanent measurements in the taking-off-domains'.** High precision relative measurement systems (borehole tilt-meters, extensometers, hydrostatic levelling systems, etc.) can be installed in a cost saving way in the area of the taking-off-domains to obtain online information about the geodynamical process (see Sec. 4). This multi-sensor system can measure continuously and can therefore support the real time alert system in this application.

3rd step: **'Impact and risk assessment; development of strategies for knowledge-based alert systems'.** The integration of hazard and vulnerability analysis leads to an estimation of the actual risk situation of the affected population. The risk management measures also depend heavily on the specific conditions and include landuse planning, technical measures (e.g. building drainage systems), biological measures (e.g. afforestation) and temporary measures in case of danger.

Three tasks of the project are described below in more detail.

2. GIS integrated geological evaluations of remote-sensing data

The goal of this step is the delineation of high-risk areas in regions with a greater number of landslides. Remote sensing technology embedded in a GIS database can be used as a complementary tool for existing landslide hazard studies, [3]. In the OASYS project LANDSAT ETM, ENVISAT, and ERS imageries are used to produce maps within a 'Landslide Hazard Information System' as layers in a GIS data base with the aim to create user-defined computations of landslide hazard maps. By using earth observation data it is possible to detect traces of past or even recent tectonic movements and mass movements which could be sources for future landslides.

Especially 'Lineament Analysis' based on LANDSAT ETM and radar images can help to delineate those local fracture systems and faults that might influence dynamics and shape of landslides. In this case digital image enhancement is an important step followed by visual interpretation in an interactive manner.

Aim of these techniques is to detect linear or curve linear features in order to find traces of possible slope failure. Combining lineament maps for example with slope degree maps, derived from digital terrain models, helps to delineate areas with higher risk. The term lineament is used for all linear, rectilinear or slightly bended image elements being extracted by image enhancement. Lineaments are symbols for e. g. linear valleys, linear zones of abundant watering, drainage network, peculiar vegetation, landscape and geological anomalies. The definition of the borders of landslide areas can be based on the assumption that lineament systems in a satellite image are closely connected to deformation which is caused by a change in the Earth´s crust stress field.

3. Geometrical analysis of monitoring data with fuzzy systems

One aim within the integration of different measurement methods was the precise, continuously monitoring of the taking-off-domains with geotechnical sensors. This information can be used in the alert system to analyse the actual situation.

So one task was the detection of block boundaries between stable and unstable areas or between unstable areas (moving with different velocities in different directions) out of the displacement vectors given by the geodetic deformation measurements. These block boundaries are the optimal places for the installation of geotechnical sensors, which give a very precise relative information on the movement in this area.

Classical deformation measurements are usually done in several epochs; for processing the geodetic deformation analysis is used. This analysis results in displacement vectors for distinct points being observed in each epoch. So an advanced analysis method is necessary, using the displacement vectors for a grouping of observed points into blocks of consistent movement pattern. Within the classical quasi-static geodetic deformation analysis only single point movements can be assessed. A block detection and assessment is only possible manually, i.e. the user can define models describing different blocks, which are assessed by statistical properties (e.g. [4]). This strategy of 'trial and error' is not useful for a large number of object points. So an automated block detection method was necessary.

A pure mathematical approach cannot fully achieve this goal due to the inherent fuzziness of this problem. A human expert solves this task by looking at the graphical representation of the displacement vectors. Keeping in mind other non-mathematical relevant information like geological facts or some properties of the measurement process, he or she can separate the blocks by a combination of mathematical facts and human experience. This kind of processing can be achieved with help of fuzzy systems, where the human way of thinking can be imitated by a rule based expert knowledge.

The task is to find groups of points with a similar pattern of movement, so that the bounderies between these blocks can be identified. Within the automated block detection process, the smallest starting block of 4 points is identified due to some indicators. Then the block is expanded by an iterative algorithm, where the best fitting point is added to the block in each iteration step until no neighbouring points with a similar pattern of movement exist. Two different types of parameters are used as indicators for this block separation (for more details see e.g. [5]):

1. Geodetic parameters: an overdetermined affine coordinate transformation and the derived strain parameters are used to assess the movement pattern of the observed points. If the points of the block under investigation are lying on one block (showing a similar pattern of movement), e.g. the strain parameters and the standard deviation of unit weight of the coordinate transformation are rather small. If in the next iteration step a neighbouring point with another movement pattern is added to this block, these indicators usually are increasing significantly. But for a fully automated analysis, these geodetic indicators are not sufficient. So a second type of parameters is needed, using human expert knowledge in a fuzzy system.

2. Visual parameters: Human experts do the block detection by looking at the pattern of displacement vectors, selecting all points and the corresponding vectors which show a similar length and a similar direction. This is a typical example for the application of fuzzy systems because no sharp definition of 'similar length' or 'similar direction' can be found. One example will be given here for the indicator 'similarity of direction': If the vectors under investigation are within a range of approximately 20 gon, they can be assessed as 'similar'. The greater the difference in the azimuth, the smaller the indicator 'similarity' will be within the processing, according to the human way of thinking.

The analysis algorithm was implemented in Matlab®. The fuzzy toolbox provides the basic methods like standard membership functions, rule-based inference algorithms and calculation of the output parameters.

Some examples confirmed the applicability of the block separation algorithm in the first part of the OASYS project. Based on this information of the block boundaries, in the next step of the project the high precision geotechnical sensors can be installed in these areas.

4. FD-modelling of the test slope for a knowledge-based alarm system

4.1. Basic concept of the knowledge-based alarm system

The basic concept for a knowledge-based alarm system includes two complementary strategies for the analysis of the current state of the slope and the alarm level decision: the data- and the knowledge-based system analysis. Its architecture is described in detail in [6].

Besides the collection and investigation of geotechnical and geodetic monitoring data one central task for the data-based system analysis will be the provision of calculation results from calibrated numerical slope models which quantify the inner structure of the slope and the mechanisms of possible failure events. Numerical models can principally be represented by DE (distinct element, e.g. [7]), FD (finite difference, e.g. [8]) or FE (finite element, e.g. [9]) codes. Standard software packages are available e.g. from [10]. The slope models will aim at the calculation of the behaviour of the slope under time variable loads (e.g. mass extraction, changes in the ground-water table). In the alarm system the calculation results shall be mainly used for

- the comparison of model predictions and measured displacements to detect deviations from normal behaviour,
- the realistic simulation of failure events as reaction to critical trigger influences (possibility of prevention) and for
- the calculation of the local and global inner stress distribution of the slope which shall be used for the quantification of numerical safety factors (e.g. *FS* = factor of safety, [11]) which enable the evaluation of the risk potential.

One goal of OASYS was to accomplish a feasability study for numerical slope modelling.

4.2. Selected test slope

The monitoring system of TU Vienna (together with Geodata company) was installed at a test slope in a large open cast lignite mine in Germany. This study site provides nearly lab conditions for the development and evaluation of investigation methods for slope mechanisms, this means well known main trigger events (mass excavation process) and an also well known geological structure.

A cross section of the test slope is shown in Fig. 2. The mass extraction is realised by huge bucket wheel excavators which dig out discrete stages, so called 'berms'. The installed monitoring system for regional scale consists of two parts: a geodetic monitoring system (Fig. 2b) with GPS (GOCA = GNSS/LPS/LS-based online Control and Alarm System, see [12]) and robot tacheometers (GEOROBOT, see [13]). In addition a geotechnical monitoring system was installed in the vicinity of the current digging area (top of berm 12, see [14]). The system consists of 1 piezometer, 1 inclinometer (length ≈ 20 m), 6 accelerometers (2 systems with 3 axes each), 1 magnetostrictive extensometer and 2 tiltmeters (see Fig. 2a and [15]).

4.3. Creation of a FD model for data-based analysis

In the feasability study the slope model was restricted to static loading and the 2D-space (to avoid too extensive computing time). The idea of static loading was motivated by mass excavation as dominant trigger event and the observation of new balanced states of the slope as reaction. The numerical model was realised with the FD software FLAC3D 2.10 from HCItasca (see [16]). Its basic geometrical and physical features are

- a horizontal extension of approximately 1500 m and a vertical extension of approximately 500 m,
- a discretisation with more than 100.000 finite meshes (mean extension < 10 m),
- a density due to the geological situation and special areas of interest,
- seven physical parameters (e.g. density, Poisson ratio and bulk modulus) per mesh and
- mass extraction as main trigger event.

The numerical model was calibrated using 'trial and error methods', [16]. The material parameters were derived from geological plans and literature and adapted within a realistic range (a priori assumed uncertainty of 30 %). For this purpose calculated displacements in selected slope points (see Fig. 3) were compared with independent control measurements (e.g. precise levelling or GPS).

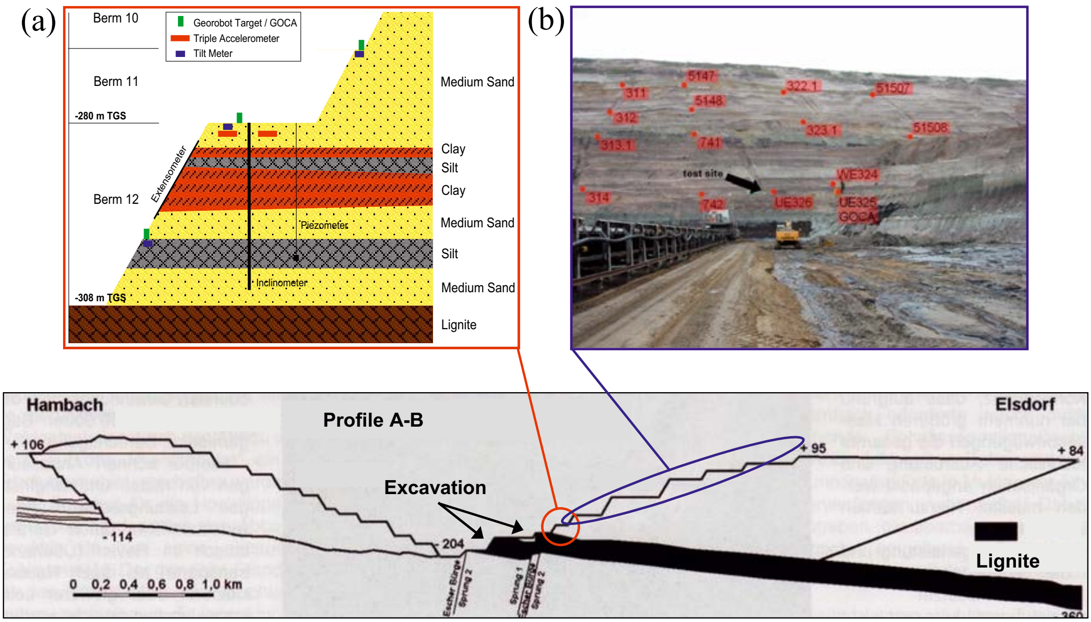

Figure 2: Test-slope with (a) geotechnical and (b) geodetic monitoring system ([14]).

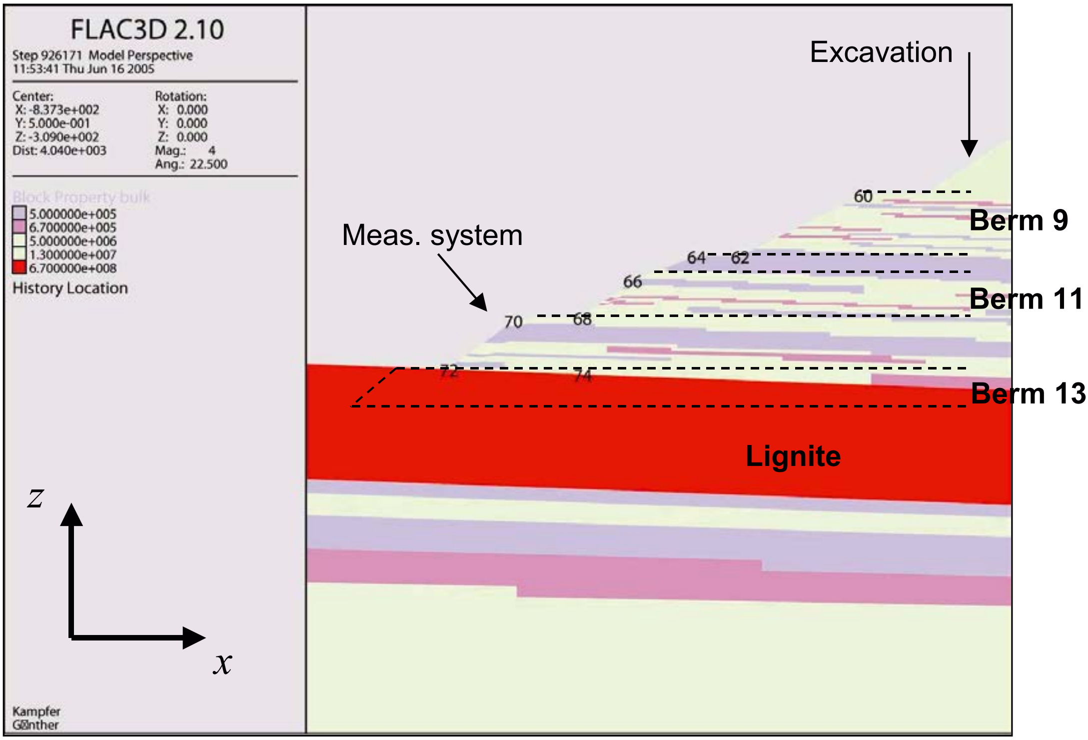

Figure 3: FD modelling of the test-slope with FLAC3D: slope points 60 to 74 (ref. to [16]).

In Fig. 3 it is also shown how the $[x,\ z]$ slope model coordinate system is defined. The x-axis defines the horizontal and the z-axis the vertical direction of the 2D slope. Positive x shows into the slope and positive z up to the zenith.

4.4. Calculation results from the calibrated FD model

In the years 2004 to 2005 trigger events were performed at the test slope by 13 excavation steps from top ground surface (tgs) down to the lignite layer (Fig. 2 and 3). The resulting berms have a mean height of approximately 30 m. In the FD model this mass extraction could be quantified by the reduction of the associated meshes and the calculation of the resulting states of equilibrium.

In Fig. 4 the comparison between predicted and monitored displacements is exemplarily shown for the sum of excavation steps 12 and 13 as trigger input. The steps were performed in mid and end of January 2005.

Control point 325 is situated on the top of berm 12 next to the geotechnical monitoring system and was not used for the calibration process. Its horizontal (Δx) and vertical (Δz) displacements are measured by a GPS receiver from the GOCA monitoring system (see Sec. 4.2). The available time series (original coordinates from GOCA output, not smoothed) start in January 2005 and end in February with a scanning rate of $\Delta t = 10$ min. They are reduced to a (nearly) static state of the slope at the beginning of January just before excavation step 12.

As a reaction to steps 12 and 13 the point rises in total with $\Delta z = 5 - 6$ cm and performs a horizontal move ‘out of the slope’ with $\Delta x \approx -11$ cm. In both cases the movements are not finally stabilised but show an asymptotic behaviour.

The related static FD prediction of the total displacements at the end of step 13 shows a contradiction of only $dx \approx 1$ cm in the horizontal and $dz \approx 2 - 3$ cm in the vertical component. Predicted and real behaviour of point 325 are fitting together within a range of some cm. These first results can be stated as promising for further attempts to predict the at least normal behaviour of the slope.

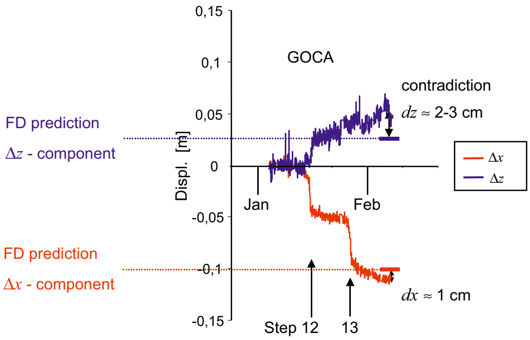

Figure 4: Comparison of FD prediction and measured displacements in control point 325.

Using the calibrated FD model it is also possible to simulate realistic failure events in instable slope areas ([16] and [17]). One simulation result is presented in Fig. 5. In the simulation the real gradient angle of the excavated berms was increased with 15 %.

Fig. 5 shows the static calculation of the total horizontal (x) and vertical (z) movement of control point 70 (also on top of berm 12) as reaction to the 13 excavation steps beginning at tgs with 0 m. The failure event starts when the lignite layer is reached by excavation and causes a horizontal move out of the slope and a vertical sagging with $\approx 1,5\,\mathrm{m}$ in each direction. Finally the movement stabilises itself again. These results could be verified by interviews with local experts which classified this combination of slope gradient, excavation quantity and mass movement as realistic.

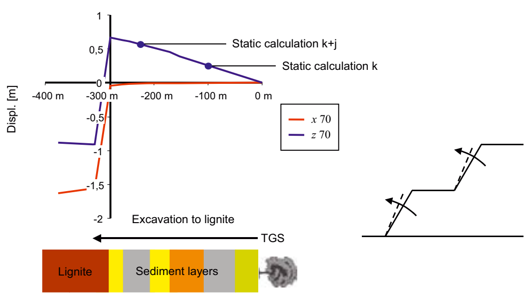

Figure 5: Simulation of a failure event: local slope sagging in control point 70 (ref. to [16]).

This example shows the potential of the calibrated numerical slope model for the simulation of failures in case of critical triggers and how to perform prevention measures. In this case one possible solution could be a reduction of the gradient angle.

5. Conclusions

A multi-scale monitoring and analysis system for detecting landslides was developed and combined with an efficient alarm system. GIS integrated geological evaluations of remote-sensing data and geometrical analysis of monitoring data with fuzzy systems enables to define the more active zones of the landslides and to install there wireless sensor networks. This concept supports cost-saving solutions especially in regions with a larger number of landslides. A concept for a knowledge-based alarm system was presented which aims to produce alarm levels by the interaction of a data- and a knowledge-based system analysis. The data-based system analysis is based on FD-modelling of the slopes which was successfully applied within the OASYS project. It can be stated that the cooperation with partners from different disciplines was the right way to investigate this complex topic. Of course further investigations are necessary to develop a functional alarm system; according research proposals are currently in evaluation.

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