COUPLING GEOINFORMATION AND SIMULATION SYSTEMS FOR THE EARLY WARNING OF LANDSLIDES

E. Nuhn [a, *], W. Reinhardt [a]

[a] Geoinformatics Research Group (AGIS), University of the Bundeswehr Munich, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany - (eva.nuhn, wolfgang.reinhardt)@unibw.de

KEY WORDS: Landslides, Early Warning, Decision Support System, Learning System, GIS, Finite-Element-Analysis

ABSTRACT:

Recurring disastrous landslides have caused great damages worldwide and many people have been affected during the last decades. Obviously there is a strong demand for developing and improving early warning systems to save lives and properties. Although numerous researches in the field of early warning systems have been made in the last years, the understanding of the hazard and the forecasting of impending events are still particularly weak points of the early warning chain. In an ongoing research project a new approach to improve these critical points in the field of early warning systems of landslides is pursued: complex simulations of landslides are coupled with geoinformation systems (GIS). This allows on the one hand for a detailed investigation of instable slopes with the help of the simulation and on the other hand for a user friendly preparation of the complex simulation results in the GIS for decision support. In this paper the interconnection between a GIS and a simulation system is introduced and two operational modes of the coupled system are presented: the learning and the decision support system. Another focus will be put on several visualization and analysis methods for the processing of the complex simulation results in a suitable way to support the user in the decision support and in the learning system, respectively.

1. INTRODUCTION

In populated mountainous regions, natural hazards resulting from large mass movements cause large human and material damages. For example, according to the international Disaster Database (EM-Dat, 2009) more than 15 000 people have been affected by disastrous mass movements in the alpine regions of Western Europe in the last 50 years. Additionally, more than 800 people lost their lives in catastrophic landslides and avalanches like the avalanche disaster from Galtür in 1999 (Wolf, 2008) or the landslide disaster from Gondo in 2000 (Pfister and Summermatter, 2004). These examples show that there is a strong demand for developing and improving early warning systems "to provide timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response" (NDMA, 2009).

During the last decades many research work has been done in the field of the prediction of landslide occurrence (e.g. Lee and Ho, 2009; Froese, 2009) and in the development of early warning systems of landslides (e.g. Zan et al., 2002; Lollino et al., 2002). Nevertheless, the understanding of the hazard and the forecasting of critical events are still particularly weak points of the early warning chain. For landslide hazards this particularly especially requires a precise predictability and an exact determination of exposure of slopes.

In order to advance research in the field of early warning systems for landslides the joint project "Development of suitable Information Systems for Early Warning Systems" was launched. The project aims at the development of components of an information system for the early recognition of landslides, their prototypical implementation and evaluation (Breunig et al. 2007, 2009). One subproject of the joint project addresses the coupling of complex finite element (FE) simulations with geo information systems (GIS) (Ortlieb et al., 2009a; Trauner et al., 2009). Numerical simulations are set-up to examine the physical processes of landslides induced by various scenarios and to improve the understanding of the causes of slope instability and triggers of ground failure. This aims at the evaluation of instable slopes and their imminent danger for human infrastructure. The coupling with the GIS allows for a user-friendly processing of the complex simulation results in the GIS for decision support.

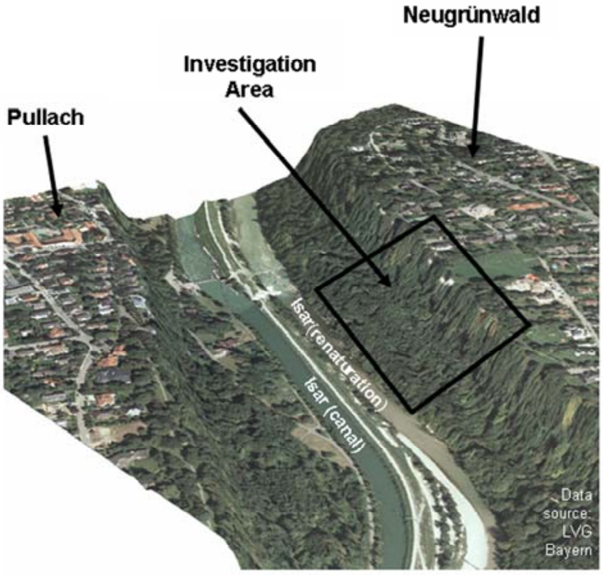

Figure 1. Application Area "Isarhänge Grünwald"

2. APPLICATION AREA

The methods developed in the framework of this project are to be evaluated on the basis of manifold data sets and specific application scenarios. Therefore a suitable application area was selected in cooperation with the Bavarian Authority of Environment. Main selection criteria was the availability of detailed geographical data and sensor measurements for a longer period of time, a coherent and comprehensive geology to verify the gained methodology in a generalized way and a potential risk, that emanates from the application area, to evaluate the system as an early warning system. A number of places in the German Alps seemed suitable as investigation areas for exemplary numeric landslide simulations. Finally a part of the slopes in the Isar valley in the south of Munich, next to Pullach and Neugrünwald, has been selected (see figure 1). In this area the Isar eroded a deep valley into layers of quaternary gravels and tertiary sediments of partially high plasticity (Trauner et al., 2008; Trauner et al., 2009). Consequently, steep and instable slopes were formed, where landslides occurred from time to time (Baumann, 1988).

In the application area, the height difference of the slope reaches up to almost 40 meters and the potentially endangered infrastructure is located close to the edge of the slope. In the early and the mid-seventies there have been several landslides in this area. As a reaction to these events and because of the risk potential several sensors (extensometer, inclinometer and ground water level tubes) were installed and geodetic measurements were initiated by the Bavarian Authority of Environment. Further, the soil layers of the slope were investigated through numerous outcrops and boreholes. Today, after more than thirty years of investigations, extensive knowledge of the subsoil structure and the failure mechanism are available and can be used in the present project.

3. SYSTEM ARCHITECTURE AND DATA FLOW OF THE COUPLED SYSTEM

At present, the application of FE-methods for the calculation of the stability of the slope is a subject of research. Due to its complexity the corresponding simulation systems are currently not available for disaster prevention and management, but would obviously be very helpful. A FE-analysis requires detailed information about the subsoil structure, the occurring soil materials, the deformation history and the stress situation of the slope, etc. Therewith the configuration of the simulation input data is very complex and usually not sufficiently supported by the simulation system. Furthermore, simulation outputs are bulky and the interpretation and analysis of the results is usually only weakly supported by the simulation system. Through the coupling with the GIS and an appropriate processing of the data, the handling of the simulation system becomes more user-friendly and intuitive. GIS can on the one hand support the preparation and selection of the input parameters and on the other hand the processing and analysis of the simulation outputs for decision support.

In figure 2 the architecture of the coupled simulation and geoinformation system is shown. The process starts with the selection and preparation of the relevant input data for the FE-analysis in the GIS. For a numerical simulation of landslides various kinds of data are needed. The following types have been identified:

- A digital elevation model,
- A three-dimensional model of the subsoil structure (a geological model),
- The boundary conditions and
- Impacting loads.

The stability and deformation of the slope is investigated within the simulation system by application of the FE-method (Trauner et al., 2009). Therefore a geotechnical model, which represents the slope in a realistic manner, has to be generated (Trauner and Boley, 2009). The area of interest, which shall be modelled, is defined by the boundary conditions. These are defined in the GIS, by selecting an area of interest for the simulation on basis of maps like topographical maps or orthopotos. The data for the description of the slope (topography and subsurface structure) is represented by a digital elevation model and a three-dimensional model of the subsoil structure.

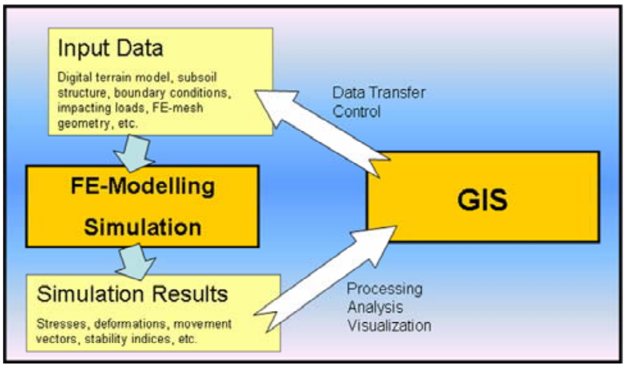

Figure 2. Architecture of the coupled system

For a FE-analysis a FE-mesh is needed. An example of a FE-mesh for a 2D-Simulation is shown in figure 3. The mesh consists of a collection of nodes and edges, which defines the finite elements, which again represents the geometry of the slope. All characteristics or attributes of the slope are then assigned to the nodes of the mesh.

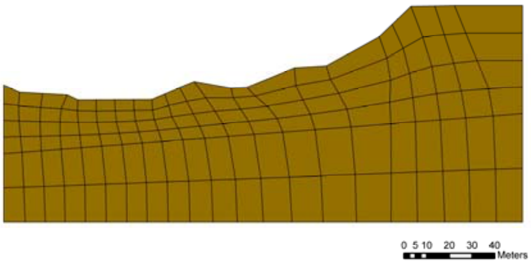

Figure 3. Example of a FE- mesh

On basis of the FE-mesh all locations of impacting loads are defined. The loads define the event, which influence of the slope shall be simulated. For example an intense rainfall event, this occurrence may destabilize the slope and cause a potential danger. The stronger these impacting loads are, the stronger are the expected deformations of the slope after the simulation.

After all required information for the FE-analysis has been collected, the data is put together in a single input file which is then the basis for computation. During the computation, the defined loads are applied incrementally on the slope and their influence at the slope stability is determined. The result of the simulation is a bulky field of vectors (e.g. deformation vectors in our test case) which indicate the instability of the slope. After the simulation these vectors are transferred to the GIS for visualization, assessment and processing into a form which is understandable for decision makers and also more handsome for experts (in case of the learning system). Furthermore, stability indices and movement vectors can be calculated from different simulation results to assess the slope stability, the likely system behaviour in future and the potential risk scenario. Additionally, rule-based GIS components support the user in the decision whether to issue an early warning or not.

4. OPERATIONAL MODES OF THE COUPLED SYSTEM

Comprehensive and exhaustive simulations are complex and computationally intensive. Like shown above, the generation of the geotechnical model needs detailed input data and knowledge about the slope formation. Furthermore, the behaviour of the slope in different conditions must be known, to use the simulation system in context of an early warning system. Therefore two main operational modes of the coupled system with differing computational costs were identified (Ortlieb et al., 2009b):

a) A learning system mode for better understanding of processes related to landslides and
b) a decision support system (DSS) mode for prevention or reaction (e.g. alert triggering) in case of a hazardous event.

The decision support system mode is primarily used by decision-makers (which could be laymen from local authorities or from emergency management) for identification of the areas at risk. The learning system mode, which is provided for experts (e.g. geologist, geotechnical engineers …), additionally supports the assessment and further GIS-based analysis of the simulation results.

The learning system enables for the evaluation of consequences of various scenarios and allows for a better understanding and prognosis of landslides. It provides the possibility to evaluate, how certain parameters influence the stability of slopes. The results of the simulations, which can be performed under varying conditions or for different time steps, can be analyzed and compared. Furthermore the learning system enables to compare observed historical events with simulated ones. Thus, critical events can be determined (e.g. a critical flood discharges). This allows for the announcement of at an early stage warnings in the decision support system mode when the critical event is expected or forecasted (e.g. intense rainfall by the weather forecast). Another functionality of the learning system is the comparison of simulations with actual measured values. This enables for the calibration and refinement of the simulations and supports the improvement of the understanding of the geotechnical characteristics of the slope. The results which were obtained in the learning system are stored in the database. This allows either for further analysis in the learning system mode or for application in the DSS (see figure 4).

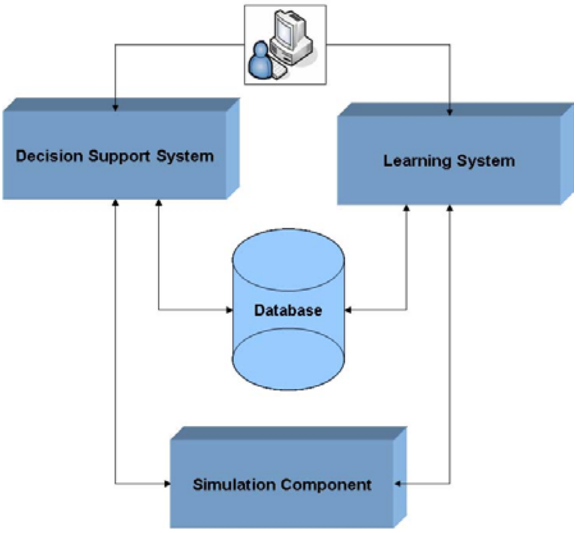

Figure 4. Architecture of the decision support and the learning system

In contrast to the learning system, the DSS is used if an acute danger exists and an immediate response is essential. This can be, for example the case of intense rainfall or an approaching flood wave, which may destabilize the slope and causes a potential danger. This occurrence requires a fast decision whether to issue an early warning or not. Because in most cases there is no time for complex and comprehensive and therefore time-consuming numerical modelling of the slope and simulation of the system behaviour, it is necessary that there is already information available in the database from previous simulations which can be used for the actual situation. If there hasn't been a simulation before a new analysis has to be carried out. In this case a simplified FE-Analysis could be executed, because an exhaustive simulation would take too much time. How this simplified simulation could be carried out with satisfying accuracy and significance is still under investigation, but tests with 2D-models are promising.

5. PREPARATION, ANALYSIS AND VISUALIZATION OF THE SIMULATION RESULTS IN THE GIS FOR DECISION SUPPORT

Results of the simulation include several parameters (e.g. stresses, strains or deformations, degree of material utilization), which can be referred to the nodes of the FE-mesh.

Figure 5. Visualized 3D simulation results

In figure 5 the results of a 3D simulation is shown. In this example the deformation of the FE-nodes are visualized as deformation vectors. To identify the important parameters, namely the deformation direction and the deformation length of the deformation vectors, the depiction has to be strongly enlarged. But therewith the overview of the whole slope will get lost.

The problem is that the simulation results are too complex and confusing to be presented like that for decision support. Therefore methodologies are needed, which allows for a user-friendly preparation and visualization, to support users in the decision support and in the learning system, respectively. In the following paragraphs such methods are investigated.

5.1 Determination of the sliding body and clustering of the complex simulation results

First, the slope has to be divided in an area where deformations occurred during the simulation and in areas with no or minor deformations. Therefore threshold values have to be defined, to determine the sliding body and the stable part of the slope (figure 6). The definition of this threshold values are still a subject of research.

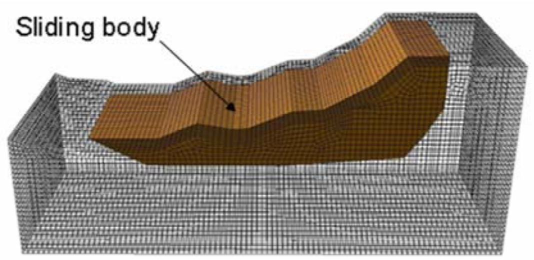

Figure 6. Identified sliding body

In figure 7 a section through the sliding body is shown. As in the 3D example of figure 5 the deformation of the FE-nodes are visualized as deformation vectors. Compared to figure 5 the deformation vectors can be distinguished in figure 7. But on the basis of this depiction no conclusion can be made, if the slope has to be categorized as landslide susceptible or not.

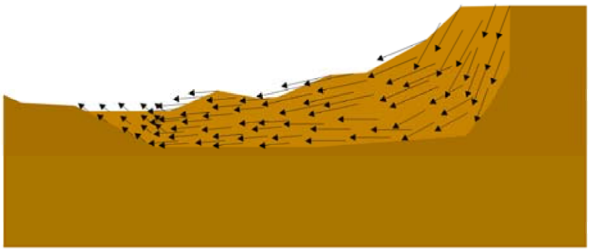

Figure 7. Deformation vectors for a 2D section of the sliding body

In the following paragraphs, a short abstract of a methodology, which allows for the clustering of the complex simulation results, is presented. The methodology is illustrated schematically on the 2D section through the sliding body. For a more detailed version see Ortlieb et al., 2009c.

The length of the deformation vectors may indicate if the slope has to be categorized as susceptible to landslide hazard or not. According to their lengths and directions these deformation vectors can be divided into classes. Afterwards clusters are detected, which include deformation vectors, belonging to the same deformation class and direction class and which are spatially adjacent.

The deformation vectors, which belong to a cluster, can be aggregated to one single deformation vector. For the aggregated deformation vectors, the area of validity has to be determined. Therefore, the FE-mesh can be used. Around the FE-nodes of the FE-mesh, which belong to a cluster, polygons are built. Result of this method is a user-friendly visualization, which presents the deformation areas of the slope with a related deformation vector (figure 8). It can be used in both modes of the system.

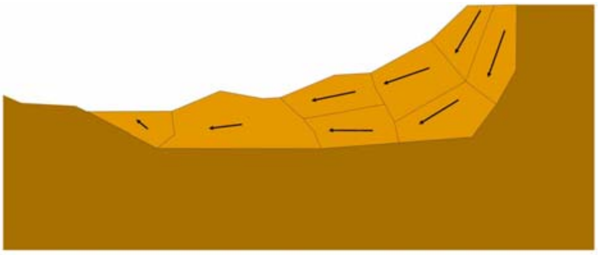

Figure 8. Aggregated deformation vectors with areas of validity

5.2 Comparison of different simulation results

While clustering of the complex simulation results provides important information for the analysis and interpretation, the changes in the clusters between different simulations are often even more meaningful for the user (Dong et al., 2003). In the learning system the user has the possibility to compare different simulation results, which were performed under varying conditions or for different time steps. To allow for a better assessment of different simulation results change detection techniques are applied to determine the important changes between the simulation results.

In Figure 9 two simulation results are shown. Both simulations were computed on basis of the same geotechnical model. Only the impacting loads were modified between the simulations. While the simulation above was computed for a rainfall event with 100 ml/m², the simulation below was computed for a rainfall event with 200 ml/m². Afterwards a cluster analysis is carried out to divide the sliding body in deformation areas. That means, each node of the FE-mesh used for the simulation is assigned to a deformation area depending on the length and the direction of the corresponding deformation vector. The membership of the node to the deformation area is expressed by a numerical value (deformation area value). For a better visualization the detected deformation areas are classified in deformation areas with small, moderate and large deformation (figure 9).

One possibility to detect the change between the two simulation results is differencing. Differencing is the subtraction of the value of the FE-node at one simulation from the corresponding FE-node value of the second simulation. To identify the nodes, which changes from one deformation area to another, the differencing is made by subtracting the deformation area values of the nodes. The differencing is done node by node to produce a visualization, which represents the change between the two simulation results. The histogram of the resulting visualization depicts a range of values from negative to positive values, where those with a zero value represents no change and the others represent the changes between two simulations. This method is widely used to detect change in several disciplines (Singh, 1989) and it is favoured because of its accuracy, simplicity in computation and ease in interpretation (Hayes and Sader, 2001).

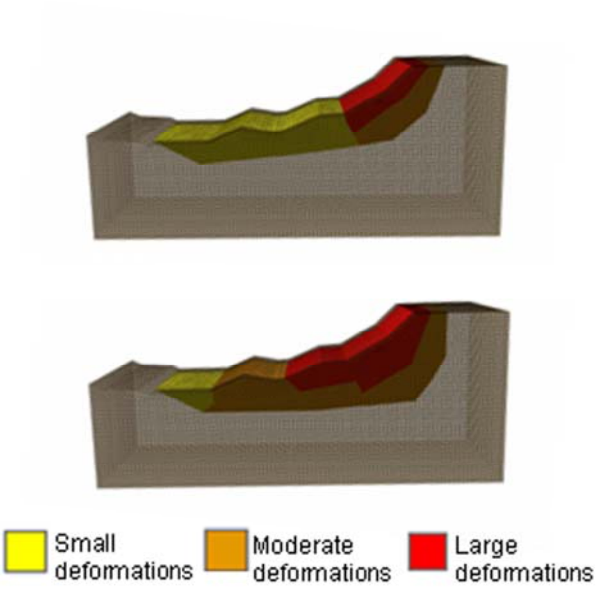

Figure 9. Simulation result 1 calculated for a rainfall event with 100 ml/m² (above) and simulation result 2 calculated for a rainfall event with 200 ml/m² (below).

Figure 10 represents the detected changes between the two simulations in figure 9 by differencing. On basis of this visualization the user of the learning system can directly identify the areas where change occurred and the areas, where no change occurred, which allows for a better assessment of different simulation results.

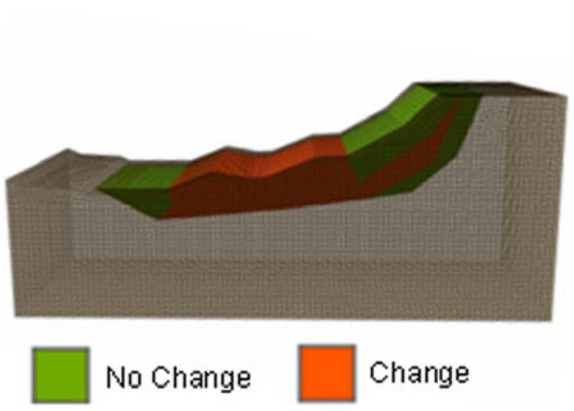

Figure 10. Detected change between the two simulation results

5.3 Preparation for Decision Support

Besides the processing of the data to produce more user-friendly diagrams, much more GIS methods can be used to support the decision-making process. The identified sliding body, for example, can be intersected with available digital topographical data (see figure 11) to determine the potential endangered infrastructure (e.g. buildings and streets). By linking the simulation results with such additional data, a decisional base for preventive measures, emergency and risk management is provided. This information can then be used to support the user in the decision-making process, whether to issue an early warning or not.

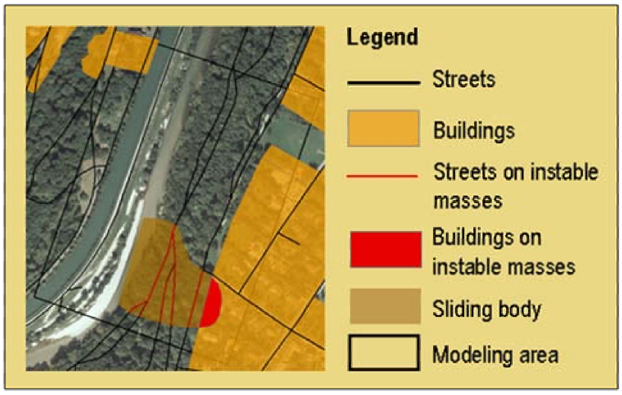

Figure 11. Determination of the potential endangered infrastructure

6. CONCLUSIONS

In this paper a coupled system, consisting of GIS and simulation system, was introduced. Further, two operational modes of the coupled system were presented: the learning and the decision support system. The decision support system mode supports decision-makers in the identification of the areas at risk, while the learning system mode, which is provided for experts, additionally supports the assessment and further GIS-based analysis of the simulation results.

Another focus of this paper was on methods for the preparation of the complex simulation results in a suitable way to support the user in the decision support and in the learning system, respectively. Therefore a clustering approach is used. This approach divides the calculated deformation vectors into clusters or classes, where similar deformation vectors (with similar deformation length and direction) are assigned to the same cluster. However, there is very often no sharp boundary between clusters so that a fuzzy clustering approach could be better suited. The suitability of such a fuzzy clustering approach, like e.g. the prominent fuzzy c-means approach (Bezdek et al., 1984), will be investigated in further studies.

Furthermore, a method for the detection and visualization of changes between simulation results was presented in this paper. With the differencing method, a method was applied, which allows for the easy identification of the areas where change occurred and the areas, where no change occurred. This GIS-based functionality allows for a better assessment of different simulation results in the learning system mode.

7. REFERENCES

Baumann, H.J., 1988. *Bruchvorgänge in Folge der Isareintiefung südlich Münchens und die kritischen Höhen der Talhänge*. Schriftenreihe des Lehrstuhls und Prüfamt für Grundbau, Bodenmechanik und Felsmechanik, Technische Universität München, 287 p.

Bezdek, J.C., Ehrlicher, R. and Full, W., 1984. FXM: The fuzzy c-means clustering algorithm. *Computers & Geosciences* 10(2-3), pp. 191 - 203.

Breunig, M., Reinhardt, W., Ortlieb, E., Mäs, S., Boley, C., Trauner, F.-X., Wiesel, J., Richter, D. , Abecker, A. , Gallus, D. and Kazakos, W., 2007. Developement of suitable information systems for early warning systems. In: *GEOTECHNOLOGIEN Science Report - Early Warning Systems in Earth Management,* No. 10, pp. 113 - 123.

Breunig, M., Schilberg, B., Kuper, P.V., Jahn, M., Reinhardt, W., Nuhn, E., Mäs, S., Boley, C., Trauner, F.-X., Wiesel, J., Richter, D., Abecker, A., Gallus, D., Kazakos, W. and Bartels, A., 2009. EGIFF- Developing Advanced GI Methods for Early Warning in Mass Movement Scenarios. In: *GEOTECHNOLOGIEN Science Report - Early Warning Systems in Earth Management,* No. 13, pp. 49 - 72.

Dong, G., Han, J., Lakshmanan, L.V.S., Pei, J. and Xu, P.S., 2003. Online mining of changes from data streams: research problems and prliminary results. *ACM SIGMOD Workshop on Management and Processing of Data Streams,* San Diego, USA.

EM-Dat, 2009. International Disaster Database. http://www.emdat.be (accessed 10.11.2009).

Froese, C.R., Jaboyedoff, M., Pedrazzini, A., Hungr, O. and Modeno, F., 2009. Hazard mapping for the eastern face of Turtle Mountain, adjacent to the frank slide, Alberta, Canada. *Landslide Processes,* Strasbourg, France, pp. 283 - 289.

Hayes, D. J. and Sader, S. A., 2001. Change Detection Techniques for monitoring forest clearing and regrowth in a tropical moist forest. *Photogrammetric Engineering and Remote Sensing* 67(9), pp. 1067 - 1075.

Lee, K.T. and Ho, J.-Y., 2009. Prediction of landslide occurrence based on slope-instability analysis and hydrological model simulation. *Journal of Hydrology* 375, pp. 489 - 497.

Lollino, G., Arattano, M. and Cuccureddu, M., 2002. The use of the automatic inclinometric system for landslide early warning: the case of Cabella Ligure (North-Western Italy). *Physics and Chemistry of the Earth* 27, pp. 1545 - 1550.

NDMA, 2009. National Disaster Management Authority - Terminology of disaster risk reduction. http://www.ndma.gov.pk/BooksPublications.html (accessed 10.11.2009).

Ortlieb, E., Reinhardt, W. and Trauner, F.-X., 2009a. *Developement of an interconnected information and simulation system*. Konferenzband Geoinformatik 2009, ifgiprints 35, Osnabrück, Germany, pp. 245 - 246.

Ortlieb, E., Reinhardt, W. and Trauner, F.-X., 2009b. Developement of a coupled geo information and simulation system for early warning systems. *Cartographie and Geoinformatics for Early Warning and Emergency Management: Towards better solutions,* Prague, Czech Republic, pp. 483 - 492.

Ortlieb, E., Reinhardt, W. and Trauner, F.-X., 2009c. *Kopplung von Geoinformation- und Simulationssystemen zur Entscheidungsunterstützung*. Mitteilungen des Bundesamtes für Kartographie und Geodäsie Band 43, Verlag des Bundesamtes für Kartographie und Geodäsie, Frankfurt am Main, Germany, pp. 97 - 106.

Pfister, C. and Summermatter, S., 2004. Katastrophen und ihre Bewältigung. - Perspektiven und Positionen, Berner Universitätsschriften.

Singh, A., 1989. Digital Change detection techniques using remotely-sensed data. *International Journal of Remote Sensing* 10(6), pp. 989 - 1003.

Trauner, F.-X. and Boley, C., 2009. Application of geotechnical models for early warning systems to mitigate threats by landslides. *17th International Conference on Soil Mechanics & Geotechnical Engineering,* Alexandria, Egypt, pp 2703 - 2706.

Trauner, F.-X., Boley, C. and Ortlieb, E., 2008. Neue innovative Methoden zur Frühwarnung auf Basis von gekoppelten Informations- und Simulationssystemen am Beispiel gravitativer Massenbewegungen. *6. Kolloquium Bauen in Boden und Fels,* Esslingen, Germany, pp. 433 - 439.

Trauner, F.-X., Ortlieb, E. and Boley, C., 2009. A coupled geoinformation and simulation system for landslide early warning systems. *6th EUREGEO Congress,* Munich, Germany, pp. 374 - 377.

Wolf, H., 2008. Lawinenunglück in Galtür. *Desaster Management - 2. Interdisziplinäres Symposium,* Schweinfurt, Germany.

Zan, L., Latini, G., Piscina, E. , Polloni, G. and Balzelli, P., 2002. Landslides early warning monitoring system. *Geoscience and Remote Sensing Symposium,* Toronto, Canada, pp. 188 - 190.

8. ACKNOWLEDGEMENTS

The funding of the research project “Development of suitable information systems for early warning systems” by the German Ministry of Education and Research (BMBF) under grant no. 03G0645A et al. within the framework of the GEOTECHNOLOGIEN initiative (http://www.geotechnologien.de) is gratefully acknowledged. This is publication no. GEOTECH-1308 of the R&D-Programme GEOTECHNOLOGIEN.