DEVELOPMENT OF A COUPLED GEO INFORMATION AND SIMULATION SYSTEM FOR EARLY WARNING SYSTEMS

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Abstract

Recurring disastrous landslides cause great damage worldwide and many people were affected during the last decades. Obviously there is a strong demand for developing and improving early warning systems to save lives and properties. Although strong efforts were made in the last decade, the understanding of the hazard and the forecasting of critical 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 finite element (FE) simulations of landslides are coupled with geo information systems (GIS). This paper will research the interconnection between the GIS and the FE-Analysis system. Further, two main operational modes, the learning system and the decision support system mode, for such a coupled system are introduced and a workflow for these system is proposed and investigated in detail.

INTRODUCTION

“Early Warning Systems include a chain of concerns, namely: understanding and mapping the hazard; monitoring and forecasting impending events; processing and disseminating understandable warnings to political authorities and the population, and undertaking appropriate and timely actions in response to the warnings” ([12]). Over the past years the evaluation of natural danger has been nationally and internationally identified as an important task and is still responding to a growing interest ([1]; [6]; [7]; [8]; [9]). Nevertheless at present the understanding of the hazards and the forecasting of impending events are particularly weak points of the early warning chain. A number of studies exist for the early warning of volcanic eruptions with sensor net approaches and for the early warning of floods ([10]; [11]; [15]; [17]). Early warning systems for landslide hazards are hardly researched. Some approaches exist with particular sensors, e.g. ground based SAR interferometer ([5]) or other sensors ([18]).

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 ([3]; [4]). One subproject of the joint project addresses the coupling of complex finite element simulations with geo information systems ([13]; [16]). 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 allows for the evaluation of instable slopes and their imminent danger for human infrastructure. The coupling with the GIS allows for a user-friendly analysis of the complex and extensive simulation results. Further, rule-based GIS analysis methods support decision-makers whether to issue an early warning.

The simulation of landslides is complex and it requires a number of manifold and extensive input information. Therefore the whole dataflow between the simulation system and the GIS is complex. In this paper a proposal for such a workflow is made and a detailed insight into it is provided.

SYSTEM ARCHITECTURE AND DATA FLOW OF THE COUPLED SYSTEM

At present the FE simulations of landslides are a subject of research. Due to their complexity the corresponding simulation systems are predominantly used by experts and scientists. For disaster prevention and management such tools are currently not available, but would obviously be very helpful. A FE simulation of a landslide requires detailed information about the subsoil structure, the occurring soil materials, the deformation and 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. On the other hand simulation outputs are extensive and complex and the interpretation of the simulation results is usually only weakly supported by the simulation system. For a broader use of simulation systems of landslides their handling should be more intuitive and user-friendly. GIS with their ability to store, manage and visualize geographical information provide a good basis for setting up the inputs of a FE simulation, analyzing and integrating the outputs and finally support a decision.

The interconnection between simulation system and GIS is schematically shown in figure 1. The process starts with the selection of relevant parameters which are needed for the simulation. The parameter transfer is controlled by the GIS. These parameters include basically geometry, the subsoil structure and several boundary conditions (see section simulation component related part of the workflow). Within the simulation system the modelling of the slope and the simulation of the landslide is executed.

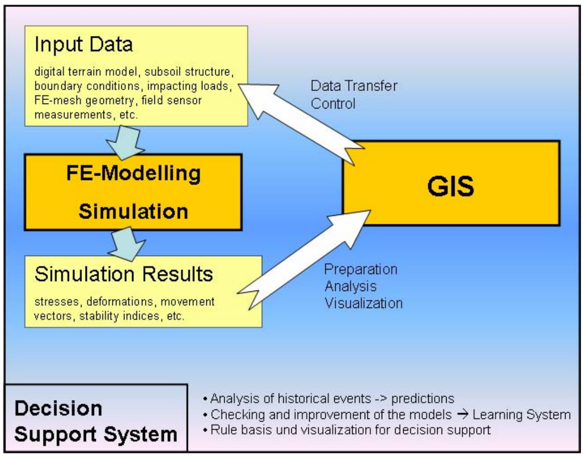

Figure 1. Interconnection between Simulation System and GIS.

After the simulation the results are transferred to the GIS for visualisation, assessment and for processing into a form which is understandable for decision makers. Furthermore, stability indices and movement vectors can be calculated from the simulation results to assess the slope stability, the likely system behaviour in future and the potential risk scenario. Uncertainties in the data used in the simulation and in subsequent processes should also be modelled and visualised in the GIS. In particular for the support of the user in the decision-making process the uncertainties have to be recognizable, in order to allow for validation of the results by the user. Additionally, rule-based GIS components support the user in the decision whether to issue an early warning or not.

WORKFLOW OF THE COUPLED SYSTEM

Comprehensive and exhaustive simulations are complex and computationally intensive and can be in case of an early warning decision too time-consuming. Therefore two main operational modes of the coupled system with differing computational costs are identified:

a) learning system mode for better understanding of landslide movements before hazardous events happen and
b) decision support system (DSS) mode for prevention or reaction after a hazardous event.

In the following sections a workflow of the coupled system is proposed. Some components of the workflow are only used by one operational mode, but there are also components which are used in both modes, namely the simulation, the database and the rulebase component related part of the workflow.

Learning System Workflow

The learning system enables for the evaluation of consequences of various scenarios and allows for a better understanding and prognosis of landslides. The learning system workflow is schematically shown in figure 2. The user has the opportunity to create a new project. Therefore he can choose an area of interest and can import relevant data, like topographical data, e.g. topographical maps. In case a project has been established already he can directly use the learning system. Afterwards he has the opportunity to investigate the slopes in the selected area of interest, e.g. the configuration of the slope, the distribution of different soil types etc. Therefore he can import geological data from the database. But the main task within this mode is to learn how certain parameters (e.g. certain amounts of rainfall) influence the stability of the slope. Therefore FE-Analyses have to be available for quite a number of cases (related to rainfall amounts). When using the learning system at first a query has to be made if a simulation already exists for the selected area of interest. There are two alternatives to search for existing simulations in the database:

- Query all available simulations for the selected area of interest.
- Restrict the query parameters.

In the latter case the user can select specific query parameters. That means in the database is only searched for simulations, which were executed with specific parameters (e.g. with certain amounts of rainfall). The query parameters include simulation parameters (see section simulation component related part of the workflow) and metadata of the simulations (see section database component related part of the workflow). If there are simulations available for the user defined query parameters, they are either transferred to the rulebase for linkage with decision rules or, if the simulation results are already prepared, directly to the learning system. If there are no simulations available a new simulation has to be calculated (see section simulation component related part of the workflow). After passing theses components the simulation results are transferred to the learning system.

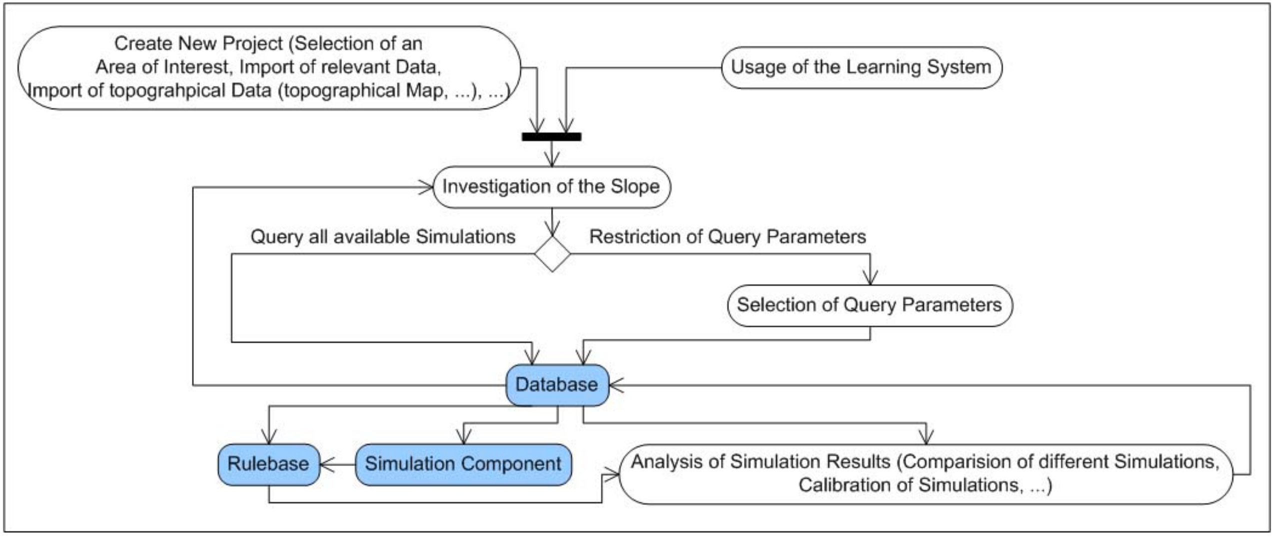

Figure 2. Workflow of the Learning System.

By using the learning system the user can analyse the simulation results. It is possible to analyse and compare different simulations in the learning system. This allows for a better understanding and prognosis of landslides. Furthermore the learning system enables to compare observed historical events with simulated ones. Thus, critical events can be determined (e.g. a critical flood discharge). This allows for the announcement of warnings at an early stage when the critical event is expected or forecasted (e.g. intense rainfall). 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 gained 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.

Decision Support System Workflow

In contrast to the learning system, the DSS is used if an acute danger exists. This can be, for example in case of intense rainfall, which may destabilize the slope and causes a potential risk. This occurrence requires a fast decision whether to issue an early warning or not. The DSS workflow is schematically shown in figure 3. Analogue to the learning system the user can create a new project or, in case a project has been established already, he can directly use the decision support system. To determine the risk potential of an ascertained area he has to enter the event which influence of the slope shall be simulated (e.g. rainfall) and actual measured values, which represent the dimension of the event. Subsequently, the user has the possibility to introduce or to adapt the metadata of these measured values. Because in most cases there is no time for complex and comprehensive and therefore time-consuming numerical modelling of the slope and simulation of landslide hazard it is necessary that there are already simulations available in the database for the actual case. Between the input of the actual measured values and the metadata by the user and the database query an intermediate step is needed. In this step the measured values are assigned to a simulation parameter (see section simulation component related part of the workflow). The assignment rules, which measured value has to be assigned to which simulation parameter, have to be predefined in the system. Afterwards the database query is performed. In case there has been a simulation before, the simulation results are transferred to the rulebase. If the simulation results are already linked with decision rules they are transferred directly to the DSS. If there hasn't been a simulation before a new simulation has to be carried out. The results of this simulation are transferred to the rulebase and afterwards back to the DSS. In the DSS the landslide susceptibility of the slope and the associated uncertainties can be visualised. In case the area of interest is landslide susceptible the user has to trigger an early warning to activate the early warning chain. Subsequently, a warning is disseminated to political authorities and to the population and appropriate actions can be undertaken.

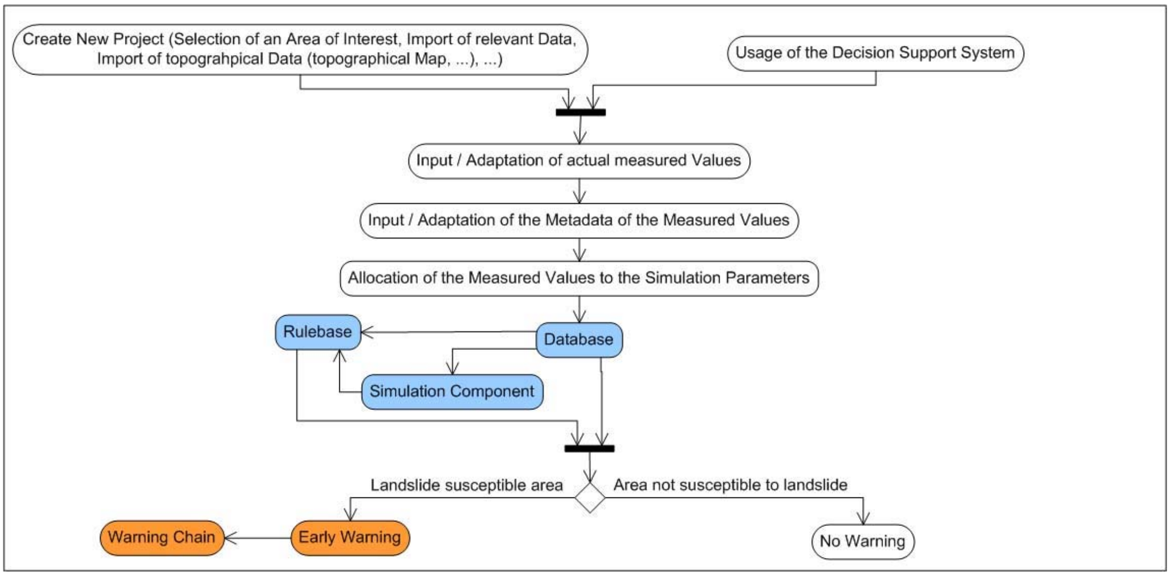

Figure 3. Workflow of the Decision Support System.

Shared Components of the Workflow

As shown above, for the DSS and the learning system a specific workflow has been defined. But there are also components, which are used in both cases. This includes the simulation, the database and the rulebase component related parts of the workflow. In the following sections these parts of the workflow are described in more detail. Because the simulation results are too complex and extensive (see section simulation component related part of the workflow) to be presented as raw data for decision support, they have to be linked with decision rules in the rulebase. Because the configuration and the workflow of the rulebase component related part of the workflow is a subject of future research it is not discussed here.

Database Component related Part of the Workflow

In the database several results from previous simulations and previous analyses are stored together with the related parameters and metadata. Simulation parameters will be introduced in the simulation component related part of the workflow section. The metadata on the other hand include for example the date of the simulation and a short description of the simulation (e. g. which event was simulated with which measured values). Additionally, results, which were gained in the rulebase, in the decision support and the learning system are stored in the database (see figure 4) to be available for consecutive investigations. The storage of the results is of particular interest for the DSS, were a fast decision is required (see section decision support system workflow).

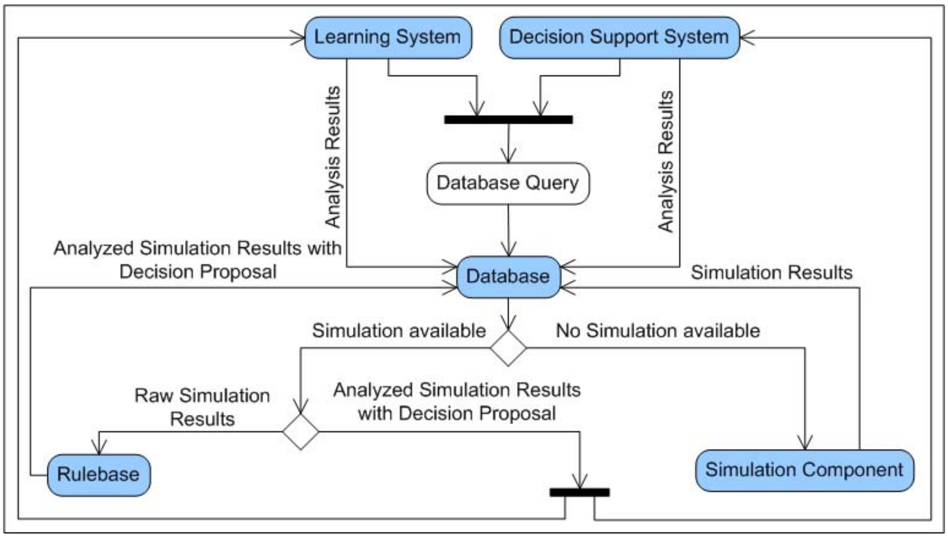

Figure 4. Database Component related Part of the Workflow.

Besides the simulation and analysis results geological and geometrical data of different slopes are stored in the database. These include the parameters required to perform a simulation, e.g. digital terrain model and subsoil structure (see section simulation component related part of the workflow). To avoid repeating simulations of the same or similar scenarios with the same parameters the simulation parameters and the metadata respectively are queried in a first step. The query parameters are defined in the decision support and in the learning system, respectively (see corresponding sections). If there are simulations available two cases are possible:

- The simulation results are already analysed and are available with a decision proposal.
- The simulation results are not analysed (raw data).

In the former case the landslide susceptibility of the slope and the corresponding uncertainties can be visualised in the GIS, to support the user either in the DSS or to provide a base for further investigations in the learning system. If only the raw simulation results are available they have to be linked with decision rules for further investigations in the rulebase. If there are no results from previous simulations available for the user defined query parameters the user can initiate a new simulation. Therefore the simulation component related part of the workflow is accessed.

Simulation Component related Part of the Workflow

The process in the simulation component related part of the workflow starts with the selection and the definition of the required input data (see figure 5). For a numerical simulation various simulation parameters are needed. Some of them are user-defined parameters and some are imported from the database. The user-defined parameters include:

- The area of investigation,
- the event, which influence of the slope shall be examined (e.g. rainfall) and
- the dimension of the event.

Since in certain cases the event and its dimension can't be directly incorporated in the simulation system an intermediate step is needed. In this step the event and its dimension are assigned to a simulation parameter, in general a so called system load. The stronger these impacting loads are the stronger are the expected deformations of the slope after the simulation.

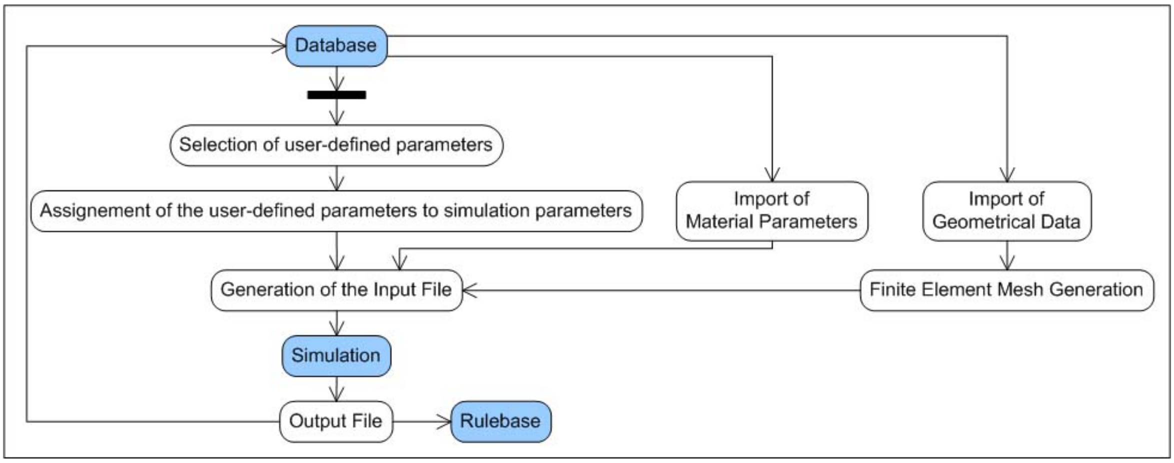

Figure 5. Simulation Component related Part of the Workflow.

Another fundamental input parameter for the simulation is a FE mesh, which represents the geometry of the slope. An example of a simple FE mesh of a 2D simulation is shown in figure 6. It consists of a collection of nodes, which define the corners of finite elements. The overall number of elements used in the FE mesh, affects the accuracy of the obtained results from the simulation. Therefore the FE mesh needs to have different resolutions at different parts of the slope. For example the area surrounding a sliding surface has been identified as an area of particular interest and should therefore be modelled with an increased mesh density. The FE mesh is calculated in a FE mesh generator. To do so two parameters are needed, which are queried from the database:

- A digital terrain model (DTM) and
- a three-dimensional model of the subsoil structure (geology).

The DTM defines the geometry of the upper model boundary of the slope. Further, the three-dimensional model of the subsoil structure defines the stratification, which gives information about the distribution of different soil layers in the slope. After the creation the mesh is returned to the GIS, where the input file for the simulation is generated. Besides the user-defined simulation parameters and the FE mesh, the material of the soil layers has also to be known for the simulation and are therefore also written in the input file. The data transfer between the GIS and the simulation system is currently file based. This means the input file for the simulation is transferred to the simulation system as an ASCII file containing the above mentioned data.

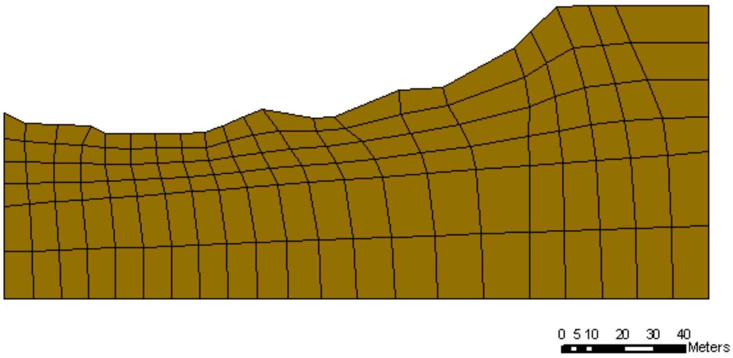

Figure 6. Finite Element Mesh of a 2D Simulation.

Within the simulation system the focus is put on numerical analyses to investigate and assess the stability of slopes. Applying different loads and exogenous scenarios, the prediction of the system behaviour, e.g. deformation and slope stability, can be achieved on basis of geotechnically and mechanically well-founded models. Compared to the approach of statistical models, the employment of physically founded models enables to take the causes and triggers of landslides into direct consideration. More details related to this issue can be found in [16].

Results of the simulation are several parameters (e.g. stresses, strains and deformations), which correspond to the nodes of the FE mesh. In figure 7 the result of a 3D simulation is shown. In this example the deformations of the FE nodes are visualised as deformation vectors. To identify the important parameters, namely the deformation direction und deformation length of the deformation vectors, the deciption has to be strongly enlarged. But therewith the overview of the whole slope will get lost.

Figure 7. Visualised 3D Simulation Results.

In figure 8 the result of a 2D simulation is shown. In this figure deformation vectors, which represent the deformation of the FE nodes, are visualised. Contrary to the 3D simulation results in figure 7, the deformation vectors can be distinguished. In the figure the deformation direction and the deformation length is shown. However, the figure doesn´t enable to make a statement about the area of validity of the deformation vectors and the susceptibility of the slope. The problem is, that the simulation results are too complex and extensive, to be presented like that for decision support. The results have to be linked with decision rules in the rulebase and prepared with a methodology, which allows for the visualization of the complex results in the learning system and the decision support system respectively in an appropriate way. In the following paragraph a short abstract of a methodology, which allows for the user-friendly visualization is presented. For a more detailed version see ([14]).

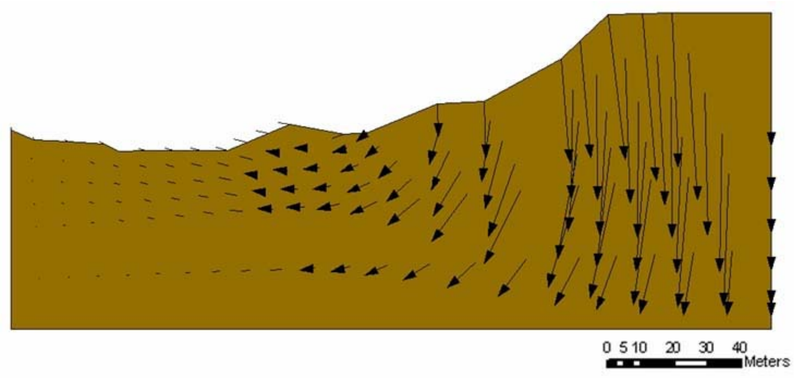

Figure 8. Visualised 2D Simulation Results.

The length of the deformation vectors indicate, if the slope has to be categorized as landslide susceptible. The length results directly from the loads, which were applied during the simulation. The stronger these impacting loads were the larger are the deformation of the FE mesh nodes and therefore the lengths of the deformation vectors. These deformation vectors can be divided according to their length into classes of susceptibility. To which class the vector belongs is defined in the decision rules in the rulebase. The division is made according to:

- Non-susceptible classes (green deformation vectors),
- classes with low susceptibility (yellow deformation vectors),
- classes with moderate susceptibility (orange deformation vectors) and
- classes with high susceptibility (red deformation vectors).

The result of the classification is shown in figure 9. Subsequently the deformation vectors are divided into direction classes. Afterwards clusters are detected, which include deformation vectors, which belong to the same susceptible class, to the same direction class and are spatially adjacent.

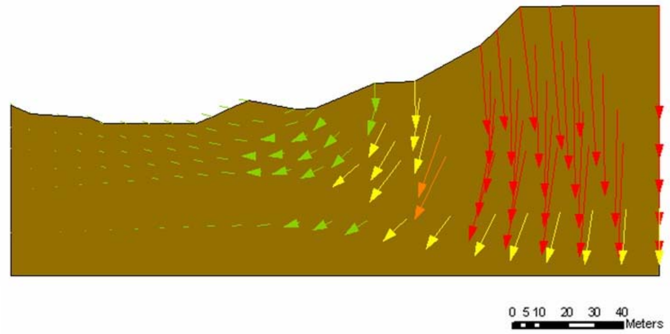

Figure 9. Simulation Results linked with Decision Rules.

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 (see figure 10). Result of this method is a user-friendly visualisation, which presents different areas of susceptibility with a related deformation vector, which represents the susceptibility class.

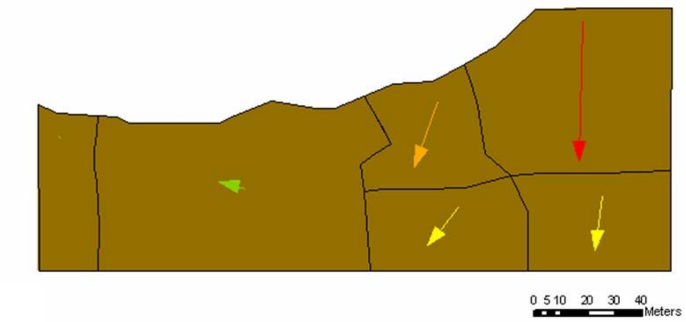

Figure 10. Deformation Vectors with Area of Susceptibility.

CONCLUSION AND OUTLOOK

In this paper a workflow for a coupled system and two modes of the coupled system are presented. At the moment the presented workflow is tested and implemented with real mass movement scenarios. Therefore a part of the hillsides in the Isar valley in the south of Munich has been selected for exemplary landslide simulations. In this area, the height difference of the slope reaches up to almost 40 meters and the potentially endangered human infrastructure is located to the edge of the slope. In the early and the mid-seventies there have been several landslides in this area. As a reaction of these events and because of the high risk potential several measuring devices were installed by the Bavarian Environment Agency. 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 ([2];[16]).

Future research will basically address the modelling of the slope and the simulation of the landslide. Another focus is put on the preparation of the complex simulation results for the support in the DSS. Therefore several aggregation and visualisation techniques for 2D and also for 3D simulation results have to be investigated. Also the risk potential of an awaited landslide has to be assessed with appropriate methodologies.

Besides the user-friendly visualisation of the simulation results corresponding uncertainties should also be modelled and visualised. In particular for presentation in the DSS the uncertainties have to be recognisable, in order to allow for validation of the results by the user. Both, the modelling and the visualisation of the uncertainties are still a subject of research in the presented project.

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REFERENCES

[1] Alexander, D. (2006): Globalization of Disaster: Trends, Problems and Dilemmas. Journal of International Affairs 59 (2), pp.1 – 22.
[2] Baumann, H. J. (1988): Bruchvorgänge in Folge der Isareintiefung südlich Münchens und die kritischen Höhen der Talhänge. In: Schriftenreihe des Lehrstuhls und Prüfamt für Grundbau, Bodenmechanik und Felsmechanik der Technischen Universität München, Heft 12.
[3] Breunig, M., Broscheit, B., Reinhardt, W., Ortlieb, E., Mäs, S., Boley, C., Trauner, F.-X., Wiesel, J., Richter, D., Abecker, A., Gallus, D., Kazakos, W. and Bartels, A. (2007): Developement of suitable information systems for early warning systems (EGIFF). In: Stroink, L. (ed.): Geotechnologien. Science Report No. 10. – 136 p., Kick-Off-Meeting 10. October 2007, Technical University Karlsruhe, pp. 113 – 123.
[4] Breunig, M., Broscheit, B., Reinhardt, W., Ortlieb, E., Mäs, S., Boley, C., Trauner, F.-X., Wiesel, J., Richter, D., Abecker, A., Gallus, D., Kazakos, W. and Bartels, A. (2008): Towards an information system for early warning of landslides. EnvironInfo 2008, Lüneburg, pp. 476 – 481.
[5] Casagli, N., Farina, P., Leva, D., Nico, G. and Tarchi, D. (2002): Monitoring the Tessina landslide bay by a round-based SAR interferometer and assessment of the system accuracy. Geoscience and Remote Sensing Symposium, Toronto, 21 – 26 April 2002, pp. 2915 – 2917.
[6] Dilley, M., Chen, R. S., Deichmann, U., Lerner-Lam, A. L. and Arnold, M. (2005): Natural Disaster Hotspots: A Global Risk Analysis. The World Bank. Hazard Management Unit. Washington, D. C.
[7] Dikau, R. and Glade, T. (2002): Gefahren und Risiken durch Massenbewegungen. Geographische Rundschau 54(1), pp. 38 – 45.
[8] Fuchs, S., Keiler, M., Zischg, A. and Bründl, M. (2005): The long-term developement of avalanche risk in settlements considering the tepmporal variability of damage potential. Natural Hazards and Earth System Sciences 5, pp. 893 – 901.
[9] Gascuel, J.D., Cani, M. P., Desbrun, M., Leroy, E. and Mirgon, C. (1998): Simulating landslides for natural disaster prevention. In 9th Eurographics Workshop on Computer Animation and Simulation (EGCAS’ 98), September 1998.
[10] Gruntfest, E., and Huber, C. (1989): Status report on flood warning systems in the United States. Environmental Management 13(3), pp. 279 – 286.
[11] Handmer, J. (2001): Improving flood warnings in Europe: a research and policy agenda. Environmental Hazards 3, pp. 19 – 28.
[12] NDMA (2008): National Disaster Management Authority. Terminology of disaster risk reduction. http://www.ndma.gov.pk/BooksPublications.html
[13] Ortlieb, E., Mäs, S., Reinhardt, W. and Trauner, F.-X. (2008): Coupling Simulations of Landslides with Geoinformation Systems for Decision support and Early Warning. Proceedings of the 11th AGILE International Conference on Geographic Information Science, Girona, Spain.
[14] Ortlieb, E. and Reinhardt, W. (2009): Kopplung von Geoinformations- und Simulationssystemen zur Entscheidungsunterstützung.

Paper accepted for: 45. AgA-Tagung, Frankfurt.
[15] Plate, E. J. (2002): Flood risk and flood management. Journal of Hydrology 267, pp. 2 – 11.
[16] Trauner, F.-X., Meyer, F., Boley, C. and Ortlieb, E. (2008): Neue innovative Methoden zur Frühwarnung auf Basis von gekoppelten Informations- und Simulationssystemen am Beispiel gravitativer Massenbewegungen. Tagungsband 6. Kolloquium Bauen in Boden und Fels, Technische Akademie Esslingen, pp. 433 – 439.
[17] Werner-Allen G., Johnson J., Ruiz, M., Lees J. and Welsh M. (2005): Monitoring Volcanic Eruptions with a Wireless Sensor Network. Proc. 2nd European Workshop on Wireless Sensor Networks (EWSN ’05), IEEE Press, pp. 108 – 120.
[18] Zan, L., Latini, G., Piscina, E., Polloni, G. and Balzelli, P. (2002): Landslides early warning monitoring system. Geoscience and Remote Sensing Symposium, 2002. IGARSS ’02. 2002 IEEE International, pp. 188 – 190.

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