Application of geotechnical models for early warning systems to mitigate threats posed by landslides

Application de modèles géotechnique pour des systèmes de préalerte pour atténuer les menaces entraînées par des glissements de masse

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ABSTRACT
The paper reports on the activities in the research project "Development of suitable information systems for early warning systems ", where, inter alia, mass movements due to slope failures in soils are analysed from a geotechnical point of view. Geotechnical models are applied to investigate causes and triggers of slope failures and to determine threshold values for the definition of critical events. To facilitate the analysis of slopes with the Finite-Element-Method, the users are assisted in the generation of simulation models by a GI system. Moreover, the GI systems provide a basis for the processing and visualization of computation results for the needs of early warning systems. Therewith the users are able to interpret the outcomes of the simulations and to assess the dangers emanating from investigated slopes. The concept is prototypically implemented for a segment of the slopes in the Isar valley south of Munich, Germany, to evaluate the developed techniques, regarding the applicability for and the improvement of warning systems for landslides, critically.

RÉSUMÉ
Cette publication rapporte les travaux dans le projet de recherche «développement de systèmes d'information appropriés pour des systèmes de préalerte», où, entre autres, des mouvements de masses causés par des ruptures du talus dans le sol sont analysés d'un point de vue géotechnique. Des modèles géotechniques sont appliqués pour étudier les causes et éléments déclencheurs des ruptures du talus et pour déterminer la valeur limite concernant la définition d'événements critiques. Pour faciliter l'analyse de talus avec la méthode des éléments finis, les usagers sont assistés dans la génération de modèles de simulation par un système d'information géographique (SIG). En plus, les systèmes d'information géographique offrent une base pour le traitement des données, la préparation et la visualisation des résultats de calculation pour l'emploi des résultats dans des systèmes de préalerte. Avec ceci les usagers sont capables d'interpréter les résultats des simulations et d'évaluer les menaces émanent des talus analysés. Le concept est implémenté de façon prototypique pour une partie des talus dans la vallée de l'Isar au sud de Munich pour évaluer de façon critique les techniques développées concernant l'applicabilité et le perfectionnement pour des systèmes d'alerte pour les glissements de masse.

Keywords: landslides, geotechnical models, early warning, decision support system, susceptibility maps, FEM, FEA, GIS

1 INTRODUCTION

Natural disasters like earthquakes, tsunamis, landslides and others periodically cause great damage. During the last century more than 4 million casualties have been recorded due to these hazards (Geotechnologien 2008). Therefore warning systems have been developed to forecast hazardous events and to protect people and goods.

For some areas, which are exceptionally endangered by landslides, sensor-data based warning systems have been set up to alert prior to an event. However these systems are not available in the bulk of endangered areas and don't provide an insight to the physical processes causing slope failures. Thus, reliable prognoses of slope deformations in future or the estimation of the point in time, when slopes may fail and landslides are initiated, is hardly possible (Trauner et al. 2008b).

As a consequence of the increasing dangerous threats by natural disasters and the strong demand for reliable warning systems the GEOTECHNOLOGIEN-initiative has been launched by the German Ministry of Education and Research. Within the project "Development of suitable information systems for early warning systems" (EGIFF) techniques to identify areas endangered by landslides and to determine critical events that may trigger slope failures are researched.

The multi-disciplinary project integrates various approaches for the early identification and investigation of landslide susceptible areas: Techniques like numerical simulations, i.e. FE-Analysis (Boley 2007, Trauner et al. 2008a), statistics and linguistic analysis methods (Gallus & Kazakos 2008, Gallus et al. 2008) are combined with or integrated in GI systems (Ortlieb et al. 2008a). In addition a central 3D/4D geo-database for the storage and management of geological spatial data (e.g. ground models) with time-related attributes (e.g. deformations, material properties, etc.) complements the overall system (Breunig et al. 2008a). For the detailed system architecture of the EGIFF project Breunig et al. (2007) refers.

In the following the idea and progress of the development of a coupled simulation and information system at the University of the Bundeswehr Munich, Germany, will be explained.

2 COUPLED GIS-FEA MODULE

The coupled system composes of a GI system (GIS) and a FEA-module (Finite-Element-Analysis module). It allows for a user-friendly and assisted investigation of the behavior of slopes due to various simulated scenarios, based on mechanically well-founded models (Trauner et al. 2008a).

2.1 *System architecture and data transfer*

As shown in Figure 1 the FEA-module is linked with the GI system in such a manner that the input data required for the set-up of geotechnical models can be received directly from the GI

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system. For that purpose the GI system sends a request to the geo-database or the users can enter missing data directly. The received data is summarized in an input file and transferred to the FEA-module afterwards. Based on this file with the geometrical definition of the topography and the structure of the subsurface, complemented with information about boundary conditions, material parameters and loads (action effects in general), a FE-mesh and finally a geotechnical model of the investigated slope can be generated (Breunig et al. 2008b). The combination of geo-database, GI system and FEA-module allows for the automatic model set-up to a large extent.

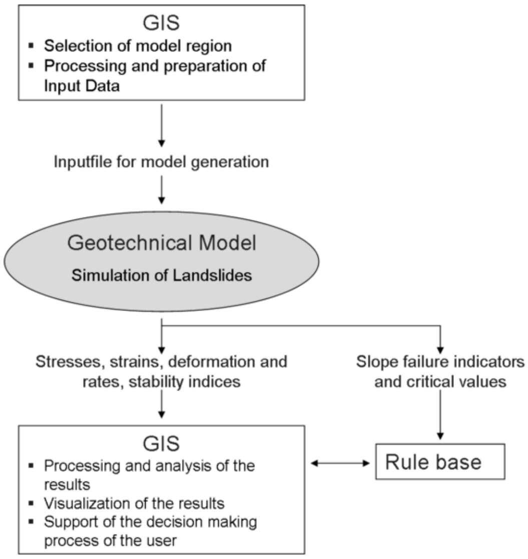

Figure 1. System architecture of the coupled system

Within the simulation component the defined action effects are applied to the modeled slope and the deformations and stress distribution due to the simulated scenario are determined. Moreover values for the critical magnitude of the simulated action effects (e.g. critical loads, critical accelerations, critical degree of material decomposition, etc.) can be obtained iteratively, if the action effects will be applied incrementally until no further equilibrium stress state can be achieved. At this stage the slope would fail and a landslide may occur. The knowledge of the critical magnitudes of the action effects that put the slope into its ultimate limit state is therefore essential for early warning purposes.

Relevant results from the analysis in regard to the assessment of the endangering by possible slope failures are written to an output file, which is transferred back to the GI system. Subsequently the data is processed and the results (deformations or deformation rates, degree of material strength utilization, safety factors, etc.) are visualized for evaluation by the user. To provide support for the assessment of the investigated situation, a rule-base with e.g. thresholds for deformation rates, is implemented within the GI system.

2.2 *Application modes*

The coupled GIS-FEM module is intended to be used for two possible fields of application: Firstly as a learning system for the better understanding of landslide formation in a specific area and secondly as a decision support system in case of expected and possibly hazardous events (Breunig et al. 2008b).

In the field of early warning for landslides one main task is the identification of the presumptive triggers for slope failures in the area under investigation. Moreover appropriate constitutive equations with respective material parameters have to be identified to be able to model the system characteristics of the slope in a reasonable and preferably realistic manner. Once the geotechnical model has been calibrated, critical magnitudes of the relevant triggers can be determined within the learning system, which are stored in the geo-database subsequently to be available, when events that may destabilize the slope, have to be assessed in future.

Another problem is the assessment of an awaited event (e.g. intense rainfalls, floodwaters, etc.) concerning the stability of a slope. In most cases the approximate magnitude of this event is known and a fast decision whether to issue a warning or not has to be made. Therefore the focus in the decision support system is put on fast performance and guidance of the user to come to a justified decision.

A detailed workflow between the GI system, the FEA-module and the geo-database for the different application modes can be found in Ortlieb et al. (2009).

3 STUDY AREA

In addition to the conceptual work, a prototype of the coupled GIS-FEA module has been implemented to evaluate the developed techniques, regarding the applicability for (early) warning systems for landslides.

3.1 *Location and situation*

The area under investigation is a segment of the slopes in the Isar valley south of Munich, Germany. In this area tertiary sediments are covered by layers of quaternary gravels, which were deposited during and after the last glacial periods.

For several millennia the Isar river eroded a valley into these deposits and the underlying tertiary sediments of partially argillaceous marl of high plasticity. According to Baumann (1988), the result was the formation of steep and instable slopes, where landslides occurred from time to time.

3.2 *Triggers and failure mechanisms*

Even though the erosion of the Isar river has been stopped for decades now, still slope failures with deep sliding surfaces can be observed in the valley. When a section of the slope fails, remains of former landslides at the foot of adjacent slopes are set into motion and are eroded by the river subsequently. Due to the reduction of the support at the base of the slope or the heightening of the slope respectively, a new failure can evolve in the adjacent areas (Baumann & Gallemann 2002). These processes may continue until the slope's gradient has been reduced sufficiently and the slopes have reached a state of static equilibrium.

3.3 *Recent landslides and measurement campaigns*

When the last slope failures were observed in the early 1970s, the Bavarian Environment Agency decided to examine these processes and to monitor the deformations in the area.

Boreholes were drilled and equipped with piezometer tubes for ground water level measurements, extensometers and inclinometers were installed and the deformations at the slope's surface have been recorded by geodetic measurements.

These devices are in the field to this day and the measurement data has been made available for the use in the research project.

4 GEOTECHNICAL MODEL

The investigations of the stability and deformation of slopes due to loads and other action effects are performed within the simulation component, i.e. the FEA-module.

Therefore geotechnical models have to be set-up, which are able to reflect the present conditions of the slope in a reasonable and realistic manner as far as possible.

4.1 *Geometry*

In a first step the geometry of the slope, which consists of the topography and the structure of the subsurface (stratigraphic or lithologic units, ground water levels, civil engineering works, etc.) has to be defined.

This task is supported by the GI system in the coupled GIS-FEA-module, as the area of interest can be selected on basis of e.g. topographical maps or master land development plans. The user can obtain further guidance by the GI system if desired, as spatial information about areas of increased landslide susceptibility can be provided. These maps are prepared by project partners, applying statistical analysis tools, which have been integrated in GI systems (Gallus et al. 2008; Gallus & Kazakos 2008), but may also originate from any other source.

Information about the structure below the ground surface can be obtained from the geo-database, wherein, in the ideal case, a three-dimensional ground model for the requested area is stored. These ground models are predominantly generated within the geo-database (Breunig et al. 2009) on basis of data obtained from site investigations (e.g. profiles form bore holes, ground water level measurement tubes, geodetic surveys, etc.) and laboratory tests, performed on material samples for the determination of material properties (e.g. densities, grain size distribution, consistency and plasticity, etc.).

In the case of a three-dimensional analysis a type of wire-frame model (Figure 2) is compiled, which includes all major structures of the slope and the surrounding area. Alternatively, two-dimensional profiles through the slope can be compiled in the same manner as described before.

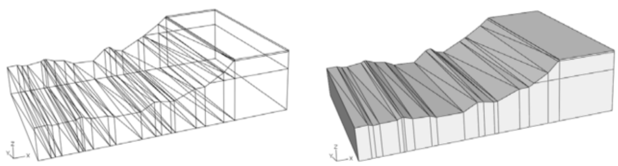

Figure 2. Wire-frame model for a section of a slope as basis for the set-up of a geotechnical model (transparent and shaded)

In subsequent modelling steps additional boundary conditions, loads (action effects in general) and other details are defined and finally a FE-mesh (Figure 3) is generated.

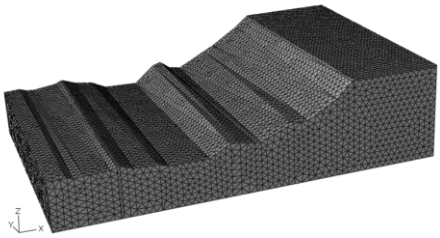

Figure 3 . FE-mesh on the wire-frame model from Figure 2

4.2 *Material definition*

To be able to simulate a slope's behaviour in large parts almost realistically, one of the most important tasks is the appropriate characterization of the material's behaviour due to the action effects under investigation.

In the case of landslides (in soils) a great variety of different failure mechanisms, which are directly associated with the appearing material, can be observed. A simple approach could, for instance, distinguish between spontaneous or abrupt slope failures with or without the indication of the failure by e.g. increasing deformation rates, and the failures, where soil masses move downhill in a relatively slow, often steady and flow like motion. Depending on these characteristics time-invariant or time-variant material properties have to be defined in the geotechnical models.

The values of the material parameters required for the appropriate constitutive equations can either be determined by field and laboratory testing or by back-analysis, both often accompanied by local experts.

4.3 *Calibration of models*

The generation of simulation models for prognosis purposes in general includes the validation and verification of these models. Prior to the deployment of the models it must be shown, that their reaction to action effects (at least for the category of interest) is similar to the ones observed in reality.

This is done during the calibration process, when events observed in the past, e.g. slope failures or slope deformations, are simulated by the model. To adjust the behaviour of the models and to bring for example calculated deformations into line with deformations recorded by sensors, several modifications may be necessary.

For that purpose it would be possible to vary values of the material parameters, change constitutive equations, modify geometries or improve the quality and accuracy of model geometries, including the density of the FE-mesh. Moreover a multitude of possibilities within the numerical solver itself are available, e.g. type of finite elements, different equation solvers, etc.

4.4 *Models for prognosis purposes*

Once the geotechnical models have been calibrated successfully for events observed in the past, it can be assumed that the models show a similar behaviour compared to the real slopes. This is at least true, as long as the triggers or action effects causing slope deformations or failures don't differ from the ones the models have been calibrated for. Henceforward, these models can be used for prognosis purposes.

Some conceivable application possibilities shall be demonstrated by the following thought examples:

Earthquakes caused several landslides in the past in a specific region. The acceleration due to the earthquakes has been recorded by sensors. As a consequence a few time-invariant models were generated for representative slope failures in that area and the material properties could be determined by field and lab testing and by the calibration of the models on basis of the observed landslides. Now the endangering of a specific slope shall be examined, which is located next to a new residential zone. A geotechnical model can be generated for that slope with the description of the material behaviour based on the parameters determined for the locations of previous landslides in this area, if no other data is available. The critical acceleration for that slope under investigation caused by an earthquake can be identified in the simulation, which corresponds to the status, when the slope reaches its ultimate stress state.

Another example is the destabilization of a slope in a river valley due to erosion of soil material at the base of the slope during flood waters. The slope has been destabilized continuously over a long period of time and is therefore under slow motion. This was already identified in the past and deformation sensors were installed at the slope. Now the deformations of the slope in future shall be estimated and the remaining period of time determined, until the slope may finally fail, because of the proceeding erosion processes. Here a (pseudo-) time-variant geotechnical model can to be set-up, although the material behaviour should be considered as constant with time, but the action effect (here the responsible trigger), namely the erosion of the riverbank, could be simplified as volume per year and running meter of riverbank. Therewith one step in the calculation may represent the geometrical change of the slope's base due to a specific amount of eroded material, which itself corresponds to a defined period of time. With the sensor-measurement data for the deformation of the slope under investigation in the past, the geotechnical model can be calibrated and a prognosis for future deformations issued. The period of time until the slope finally fails may be obtained indirectly by the determination of the maximum calculation steps (which is equal to the number of the erosion steps) until the slope reaches its ultimate limit state.

Beside the time-invariant and pseudo-time-variant simulations, truly time-variant models may be necessary in some cases. So for instance, if action effects change with time (e.g. increasing saturation of the soil as a consequence of rainfalls or seepage) or if the material properties are not constant, which is e.g. the case with degrading materials.

Moreover, the examination of a combination of several triggers for a slope in both, time-invariant and time-variant simulations, is imaginable, but would certainly strongly complicate the investigations.

5 CONCLUSIONS

The application of geotechnical models to simulate and examine physical processes causing slope failures, which may result in landslides, in a coupled GIS-FEA-module allows for the enhancement of early warning systems.

Calibrated models can be applied to determine critical values of action effects that may trigger landslides. Thereby it is of great importance to satisfy the requirement of the geotechnical models to behave similar to the slope in reality.

The conception of the module with its possibility for connection to other modules based on different approaches (statistics, analytical computation methods, etc.) via geographical information systems (GIS) and the integrated assistance functions for decision-makers provide a user-friendly and reliable medium for warning purposes.

Due to the cooperation with the Bavarian Environment Agency the results of the research project can be of avail for the public.

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