Identification of landslide susceptible slopes and risk assessment using a coupled GIS-FEA-module

Franz-Xaver Trauner[1], Conrad Boley[1] and Eva Nuhn[2]

[1]Institute for Soil Mechanics and Geotechnical Engineering, University of the Bundeswehr Munich, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany; franz-xaver.trauner@unibw.de, conrad.boley@unibw.de
[2]Geoinformatics Research Group, University of the Bundeswehr Munich, Werner-Heisenberg-Weg 39, 85577 Neubiberg, Germany; eva.nuhn@unibw.de

ABSTRACT: Natural disasters like landslides periodically cause many casualties and great damage. Therefore warning systems have been developed to protect people and goods. But to be able to set-up and to apply these systems, landslide susceptible areas have to be identified first and appropriate methods for hazard and risk assessment must be provided.

In the research project a coupled module, consisting of a geographical information system (GIS) and a Finite-Element-Analysis-tool (FEA) for the investigation of slopes has been developed. Therewith, potentially instable slopes can be analyzed from a geotechnical point of view. Physical processes, which may lead to slope failures and may cause the development of landslides can be investigated in detail. Moreover, the possibility to define criteria indicating slope failure and to determine critical magnitudes of events is supported by the module.

The set-up of geotechnical models for FE-Analyses is supported by the GIS as well as the evaluation and visualization of the computation results. Advanced visualization and analysis methods, regarding the hazard and risk assessment of slopes are merged in a decision support system integrated in the GIS to support decision-makers in time.

INTRODUCTION

An increasing number of catastrophic landslides caused great damage worldwide during the last decades. Thus, more and more warning systems are installed for some exceptionally endangered areas, mostly based on deformation sensor measurements to alert prior to an event. However these systems are not available for the bulk of endangered areas and don't provide a deep insight to the physical processes causing slope failures. Thus, reliable and mechanically well-founded prognoses of slope deformations in future or estimations of the point in time, when slopes may fail and landslides are initiated, is hardly possible.

As a consequence, the GEOTECHNOLOGIEN-initiative has been launched by the

German Ministry of Education and Research to enhance information systems for the purpose of early warning to catastrophic events.

Our research work is carried out jointly by the Institute for Soil Mechanics and Geotechnical Engineering and the Geoinformatics Research Group at the University of the Bundeswehr Munich. It is part of the multi-disciplinary project "Development of suitable information systems for early warning systems", which combines approaches from the fields of geology, geotechnics and geoinformatics for the identification and investigation of landslide susceptible areas and the early warning of disastrous events. Therein, our work is enriched by statistical and linguistical analyses (Gallus et al., 2008) and a 3D/4D geo-database for the storage and management of spatial and time-related data (Breunig et al., 2009). For detailed information on the joint project Breunig et al. (2007) refers.

GIS-FEA-MODULE

For investigations of slopes the method of Finite-Element-Analysis (FEA) is applied. This analysis tool is combined with a geographical information system (GIS) to enable a user-friendly and assisted investigation of slopes regarding their stability and susceptibility to the development of landslides. Influences of various action effects (e.g. loads, accelerations, geometrical changes, etc.) on the stability and deformation of slopes are examined in numerical simulations, while the set-up of the geotechnical models and the processing and assessment of computation results is supported by the GIS component (Fig. 1).

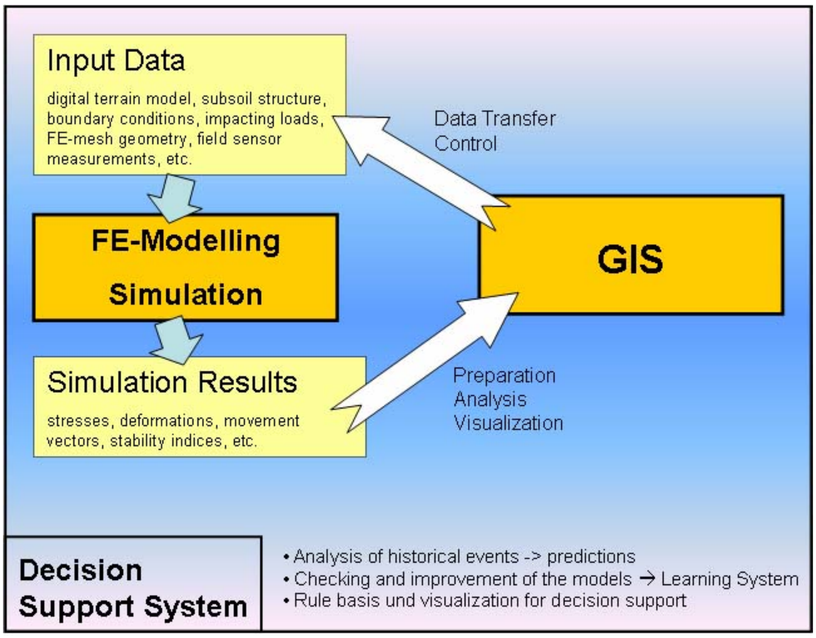


FIG. 1. Architecture of the coupled GIS-FEA-module

When an area on local scale shall be examined in detail, first the respective area of interest is selected within the GIS on basis of topographical maps, orthophotos or land development plans (Fig. 2). But of course, any other source may be chosen, which may, for instance, already suggest the distribution of increased landslide susceptibility determined by statistical analyses.

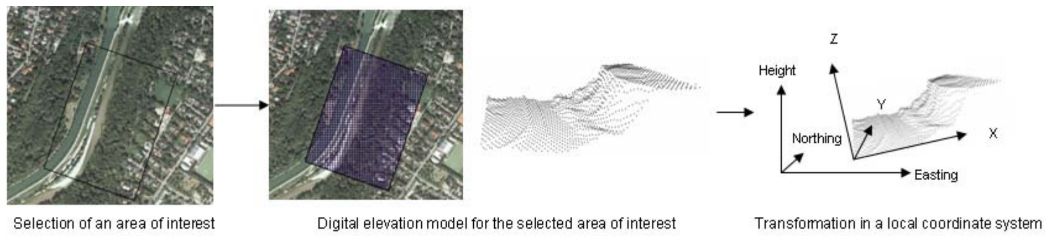


FIG. 2. Selection of the area of interest within the GI system

Thereafter the topography of the slope is extracted from a digital elevation model and supplemented with information about the subsoil structure, e.g. stratigraphic or lithologic units, ground water levels or civil works, either by query to a data base or by direct entry of the user. The data base stores all information about the subsurface structure like data from site investigations (e.g. profiles from bore holes, ground water level measurements, geodetic surveys, etc.) and field or laboratory tests (e.g. densities, grain size distributions, consistency and plasticity, etc.).

Finally, the geometrical description is supplemented by boundary conditions, action effects and other details to compile the geotechnical model of the slope. A simplified three-dimensional model for a segment of the slopes in the Isar valley south of Munich is shown in Fig. 3. Alternatively, two-dimensional profiles can be compiled in the same manner as described above.

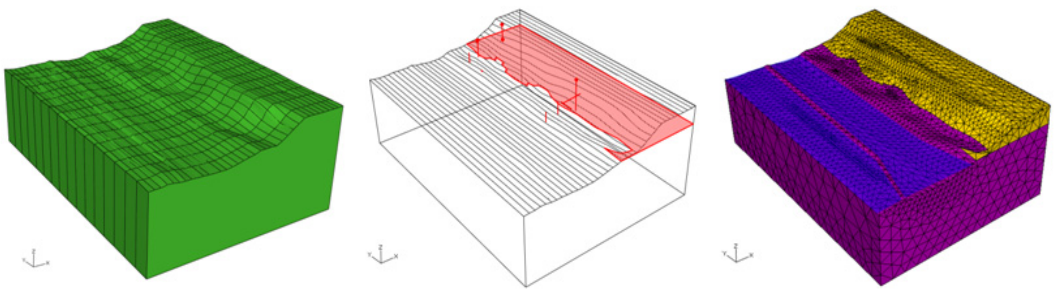


FIG. 3. Generation of the geotechnical model for FE-analysis

The stability and deformation of slopes due to action effects are investigated within the simulation component by Finite-Element-Analyses. Therefore geotechnical models, which represent the slope in a realistic manner to a large extent, have to be generated.

For modeling of slopes in a realistic manner, an appropriate characterization of the material involved is essential. Since different materials favor different failure mechanisms, the geotechnical models have to reflect this association. Therefore the decision between time-invariant or time-variant models has to be made considering both, the material's characteristics (change of material properties with time, e.g. degrading materials or dependence of strength on moisture content) and the probable failure mechanism (e.g. spontaneous failure or creep deformations).

The generation of models for prognosis purposes includes the validation and verification of these models. Prior to the deployment of these models it must be shown that their reaction to implemented action effects is similar to the ones observed in nature. This is assured during the calibration process, when events observed in the past, e.g. prior slope failures or slope deformations are simulated with the geotechnical model and then the computed results are compared to recorded deformations. To adjust the behavior of the models and to bring them into line with the natural slope, modifications (e.g. variation of material parameters, change of constitutive equations or degree of geometry's simplification) may be necessary.

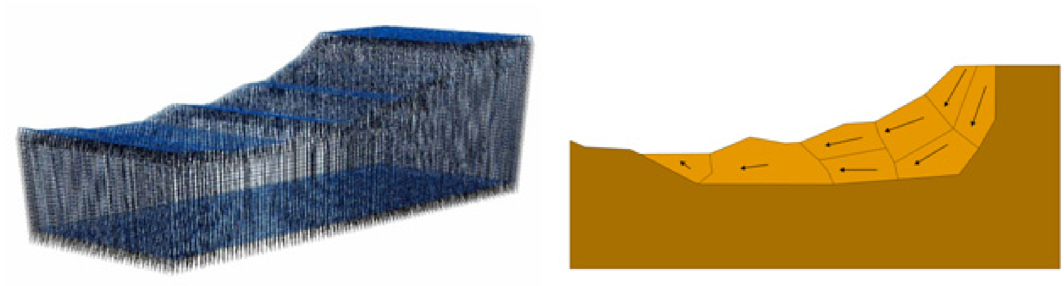
Once the geotechnical model has been calibrated successfully and shows satisfying consistency in its behavior compared to the real slope, it can be applied for prognosis purposes. The outcomes and consequences of various scenarios (characteristic deformations, change in material strength utilization, reduction of safety factor, etc.) for the slope can be determined in a simulation. Moreover the simulations can be used to determine critical magnitudes or thresholds for loads, accelerations, ground water levels or any other action effects. The knowledge of these thresholds is essential for early warning and purposes and hazard management, since they characterize the slopes' ultimate limit states.

Subsequently to the simulations, relevant computation results regarding the assessment of the endangering by possible slope failures, are compiled in an output file and transferred to the linked GIS for further processing and visualization of the data. Typically, the significant output variables are strains or deformations, deformation rates in the case of time-variant simulations, degrees of material strength utilization or local and global safety factors. But also data indicating failure mechanisms or particularly weak and highly stressed zones provide information about the system characteristics and probable type of failure. To support the assessment of the results, a rule-base containing, for example, thresholds for critical deformation rates is established within the GIS and assists users in similar situations in the future.

A main focus within the project is put on the data preparation and visualization in such a manner that the results are understandable and useable for decision makers.

DATA PREPARATION FOR DECISION SUPPORT

The outputs of the simulations are extensive and may confuse, if no assistance is provided how to obtain the required information to support a decision. A simple but plausible example is the determination of deformation vectors, representing the movements of the nodes of the meshed geotechnical model (Fig. 4a).



a) b)

FIG. 4. Deformation vectors on nodes of meshed geotechnical model

Usually it is not of great importance to have deformation vectors covering the whole model, but to distinguish between regions of different movements, both regarding the magnitude and direction.

Therefore methodologies have been developed to organize deformation vectors in classes for cluster identification (Ortlieb et al., 2009). A cluster defines a region characterized by points of comparable movements, i.e. similar direction and magnitude of deformation, and which are adjacent to each other. As a result, one deformation vector for each cluster is obtained and can sufficiently show the dominant deformation characteristics of a slope. A simplified two-dimensional example is given in Fig. 4b. In addition, this methods allow the determination of the boundary of the sliding bodies, to separate the surrounding area with no or minor movements or to calculate the depth of a sliding plane or total volume of instable masses.

Moreover, the processed computation results can be enriched by additional data from any other resources in the GI system to support the decision-making process. This information can be used in conjunction with the cluster identification to identify buildings or structures on and close to the sliding bodies (Fig. 5).

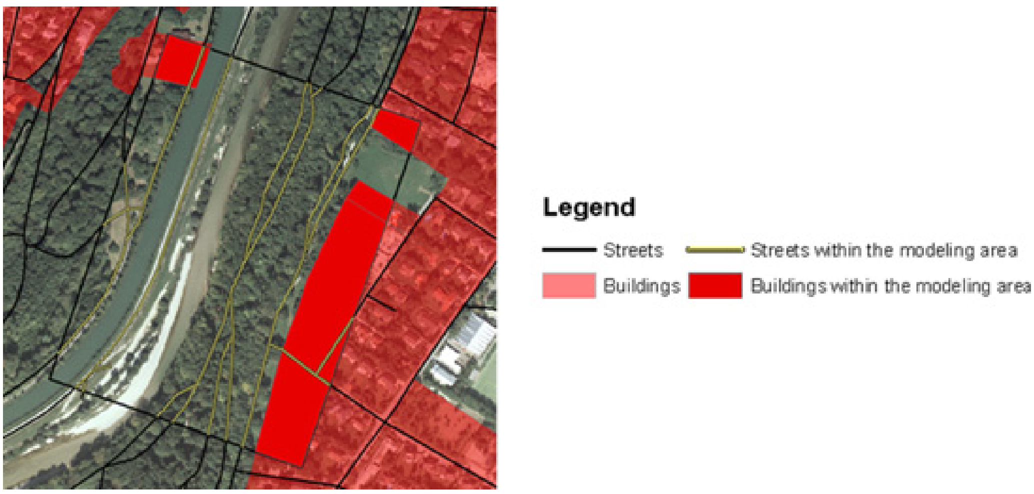


FIG. 5. Modeling area with overlain topographical data

CONCLUSIONS

The application of the GIS-FEA-module allows for the geotechnical-based determination of stability indices and thresholds for slope failures and therewith facilitates the identification of landslide susceptible slopes. The user-friendly set-up of the system including a GIS environment allows for a quick set-up of the geotechnical models compared to conventional approaches and assisted analysis of computation results to support decision-makers in the hazard management and risk assessment.

The conception of the module with its possibility for connection to other modules based on various approaches (statistics, analytical computation methods, etc.) via GIS and the integrated assistance functions for decision-makers provide a user-friendly and reliable medium for warning purposes and contribute to the reduction of threats posed by landslides.

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