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(RESEARCH ARTICLE)

Analysis of hazard potential of landslides using geo-information system

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Abstract

Natural slopes as well as man-made slopes can pose risk to human life and infrastructure with regard to its long-term stability. The still growing urbanization pressure and the infrastructure expansion, which is important from a world-wide as well as an economic point of view, means that more and more, from a geotechnical point of view, unsuitable areas are being opened up for development. Such areas are often insufficiently protected against natural disasters such as landslides.

Landslides cause world-wide enormous destruction and hence high costs for mitigation and rehabilitation. In Germany the destruction due to landslides amounts to few hundred million Euro every year. Even though, there is no spatial information about the hazard potential of areas at risk of sliding. In this paper an analysis method for risk of sliding is presented that can be integrated in a "Technical Information System" and visualized in scale 1:25000 to 1:10000 by Geographic Information System (GIS). In doing so and considering the boundary conditions, relevant criteria are combined, overlaid and merged by using rule-based algorithms. GIS-based overlay functions have been used extensively for the production of landslide hazard maps [1]. Further assessment can be performed by integrating data mining methods.

The first step in the workflow is to identify safe areas and eliminate these areas from further analysis. As results of this process, areas prone to sliding risk are focused on for further analysis. An example from Germany is used to demonstrate the process.

Keywords: Landslide; Risk analysis; Hazard map; Geotechnical engineering; Geo-information

1. Material and methods

Hazard maps based on technical information system can help in urban planning and thus save capital losses. An appropriate tool to visualize the results of sliding risk analysis is GIS. This combination offers a powerful tool for hazard analysis. In the course of the analyzing process 5 steps are to be performed, in which increasingly number of parameters are considered that effect the slope stability:

- Primary stability analysis
- Sensitivity analysis and failure mechanisms
- Trigger mechanisms
- Probability of failure
- Data mining methods
- Hazard and risk analysis

With increasing level of detailed analysis, the investigation scale shifts from the small scale to the larger scale e.g. 1:

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10,000. The aim of the individual steps is to gradually delimit areas at risk of sliding in the course of the process and thus to reduce the workload of locally required parameter surveys in the field to a minimum.

1.1. Primary stability analysis

In this first step, the aim is to use existing data about the geology, morphology and history of the area to delimit the areas that are stable according to the available data. Helpful in this regard is a slope inclination analysis by using a digital terrain model with high resolution, e.g. 10m by 10m grid size and available data of terrain structure. As results, plain areas and inclined areas less than 10° can be considered as stable areas (Figure 1).

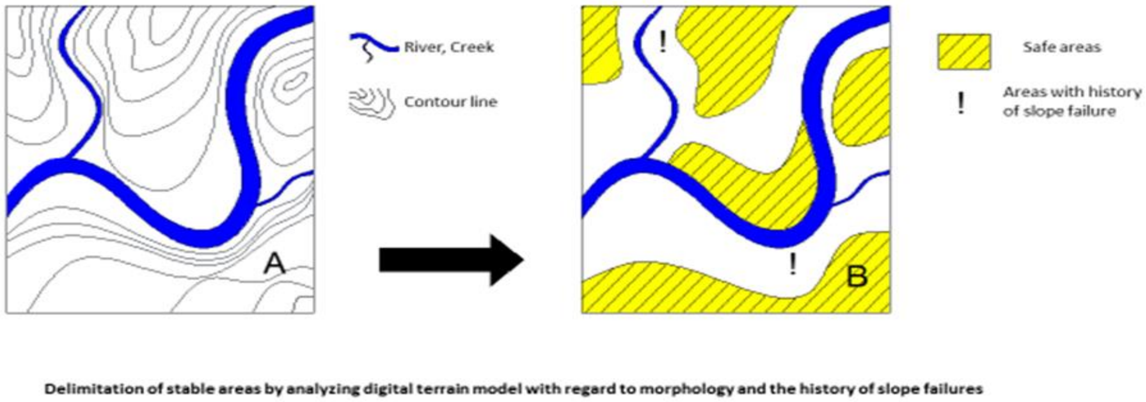
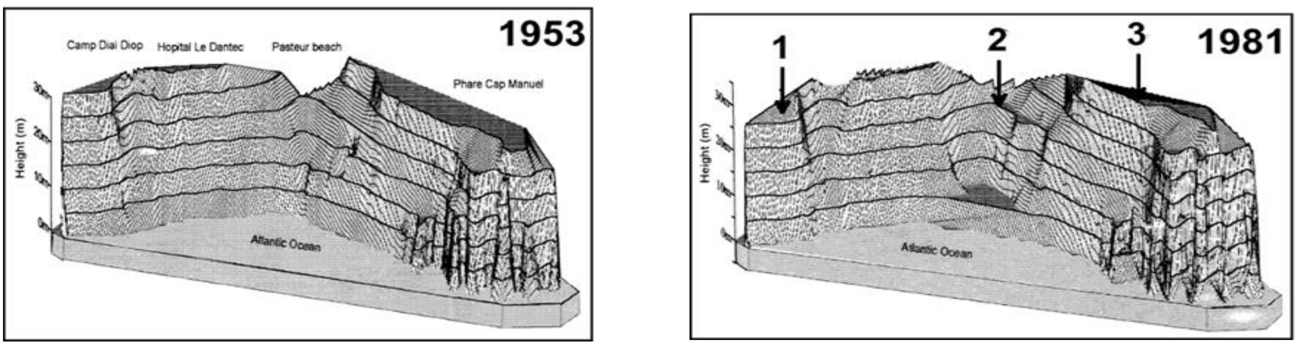


Figure 1 Delimitation of stable areas

Furthermore, a comparison between old morphological images and recent terrain models shows that possible material losses can be helpful in identifying landslide-prone areas (Figure 2) [2]. For the rest of the areas it is then important to process morphological and geological data to differentiate between soil and rock. This is necessary since when identifying a slope failure, relevant failure mechanisms must always be considered. In case of soil slopes, the lithology and soil-mechanical properties allow to identify further stable zones considering worst-case-scenarios. For the characterization of the hazard potential of the remaining soil slopes further parameters need to be integrated.

A primary evaluation of the stability of the remaining rock slopes can only be made after identifying the failure mechanisms in different zones. Special attention must be paid to the zones that build the interface between soil and rock, as in these areas many destabilizing processes take place.



1 Cliff fall and transport of the slid mass by the sea; 2 Slides and building of accumulation zone at the slope base; 3 Region developed for settlement; no visible morphological changes of the basalt cliffs [2]

Figure 2 DTM of Cap Manuel Dakar, Senegal in year 1953 compared to DTM from 1981 according to Fall et al**.** [2]

1.2. Sensitivity analysis and failure mechanisms

The aim of this step is to identify the failure mechanisms of the remaining zones/slopes from step one that have been evaluated as potentially hazardous areas. To this end, further basic data on hydrogeology, geological structure, exposure and soil as well as land use are evaluated.

As a result of the sensitivity analysis of further input parameters, the method is to be optimized in such a way that complex new data to be ascertained in the field, can be kept to a necessary minimum while the risk assessment remains meaningful.

When analyzing the stability of the remaining solid rock slopes, in addition to the rotational sliding, the failure mechanisms of 2-dimensional and 3-dimensional sliding as well as failure due toppling or drifting have to be differentiated and considered.

While mass movements are more strongly bound to steep slopes or cliffs as a result of the latter mechanisms, 2- and 3-dimensional sliding are primarily controlled by exceeding the existing shear strengths on the joint surfaces of the rocks. With geometrical considerations, the worst-case scenario can again be used to assess such surfaces as stable, if it can be proven that the lithological shear strength as a result of the slope tendency is not exceeded.

From the digital intersection of slope inclination and orientation with dip and azimuth of the dip of the interface structure, slopes can be identified as stable due to further geometric considerations (see Figure 3). Due to the very heterogeneous data situation with regard to the interface structure, one moves in the border area of what can be derived based on existing input data with regard to a stability analysis.

When the second sub-goal is reached, the areas are endured for which larger-scale evaluation requires more extensive data acquisition. This data acquisition, which mainly focuses on the determination of discontinuities structure, is carried out for the area of interest in order to create an optimal data basis.

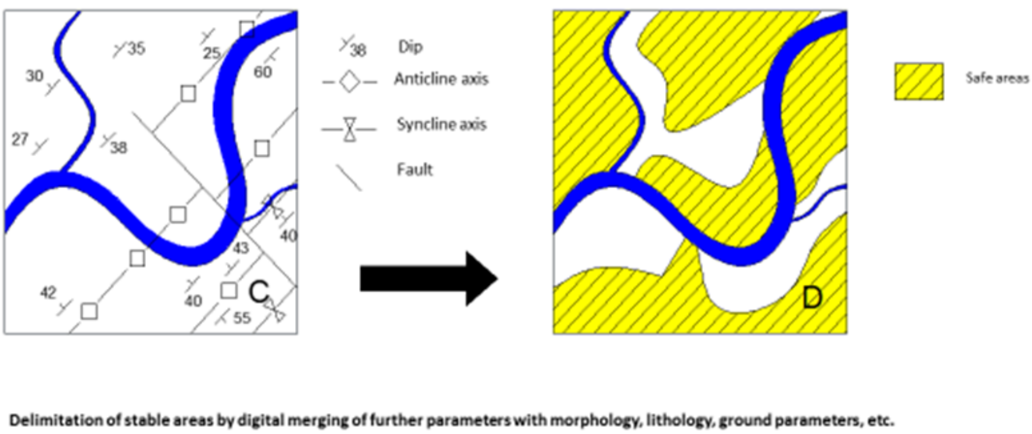


Figure 3 Merging further parameters to rule out stable areas

1.3. Trigger mechanisms

In addition to assessing static stability, dynamic processes also play a major role in destabilizing slopes or embankments. These processes are usually triggered by recurring natural events and then often lead to sudden failure.

As a third sub-goal, the identification and evaluation of the influence of trigger mechanisms is of great importance. These trigger mechanisms extend from triggers that are limited in time, e.g. the occurrence of earthquakes or heavy rainfall up to latent boundary conditions such as of land use. In a basic work, possible triggers have to be identified and their temporal but also lateral influence on the area under consideration has to be characterized. Area-specific trigger mechanisms and their probability of occurrence must be taken into account. To determine these probabilities, historical data e.g. on climate or seismicity for a particular area should be evaluated. In addition, the evaluation of theoretical scenarios and worst-case assumptions also offers the possibility of characterizing the influence of trigger mechanisms.

1.4. Probability of failure

In the fourth sub-goal, the first three sub-results, i.e. the stability analysis, the identification of failure mechanisms and the probability and impact of trigger events, are merged together across the board for the area of interest. In addition to the delimited large areas of stable slopes and embankments, there remain small areas that pose a risk of slipping.

The aim of the fourth sub-step is to develop a concept for the extensive presentation of the risk of slipping. Various scenarios can be documented based on the display options of a GIS. For example, the influence of the trigger mechanisms is shown separately or worst-case scenarios are presented.

The result is presented in the form of risk maps on a scale of 1: 10,000. The areas are broken down into risk classes, indicating the most likely failure mechanism (see Figure 4).

The presentations are to be understood as the basis for planning, which, in addition to the critical slope areas, also allow the workload required for further detailed assessment to be estimated or, in conjunction with a risk analysis (see sub-goal 5), disclose the urgency for stabilization measures.

1.5. Data mining methods

Kallash (2007) has developed an integrated method to assess the hazard potential of landslides utilizing expert knowledge and data mining methods [3].

As for a mass movement event many factors interact with each other at different levels in different times, the problem of such mass movement corresponds to a Multi Criteria Problem (MCE), so that this method can be used in cases dealing with mass movements. Since decisions have to be made on the basis of criteria, one speaks of multi-criteria decision support system. The method is used when analyzing problems with different criteria and alternatives as well as with multiple goals. This helps decision-makers to make a consistent decision out of all important subjective and objective factors [4].

According to Hwang and Yoon (1981), the multi-criteria problems are divided into two classes [5]. The first class refers to the Multi-Attribute Decision Making (MADM). The second class refers to Multi Objective Decision Making (MODM). The MADM method solves the problem by selecting alternative courses of action, while the MODM method solves the problem by calculating an alternative.

The Analytical Hierarchical Processes (AHP) belong to the first class MADM, since they belong to the multi-criteria decision analysis. Some scientists combined GIS with AHP to assess landslide hazard [6]. AHP can be used very well in the decision regarding the hazard potential of slopes in the analysis process.

Lai, J. S. and Tsai, F. (2019) developed a systematic approach with machine learning (ML) to apply the satellite remote sensing images, geographic information system (GIS) datasets and spatial analysis for multi-temporal and event-based landslide susceptibility assessments on a regional scale [7].

He et al. (2019) used GIS-technology in conjunction with two methods for assessing landslide susceptibility (LS), namely a method using experts' knowledge and experience and a mathematical/statistical method such as analytic hierarchy process (AHP) via an AHP-weighted information content method [8].

1.6. Hazard and risk analysis

A variety of approaches have been used in landslide hazard and risk assessment and these can be classified into heuristic approach, statistical approach, deterministic approach, etc. [9].

Based on the hazard map, a risk analysis is carried out by overlaying the anthropogenic use of the investigated area, which considers damage assessment of a potential landslide (Figure 4). A GIS-based conceptual system integrated with data mining has been used for landslide hazard assessment [10].

This means that areas can be endured in zones where there is a risk of slipping, which in the event of failure will result in high economic damage.

As a result of the examination, all those areas are shown in a quick and clear form for the final assessment of the stability, more extensive detailed investigations must be then carried out.

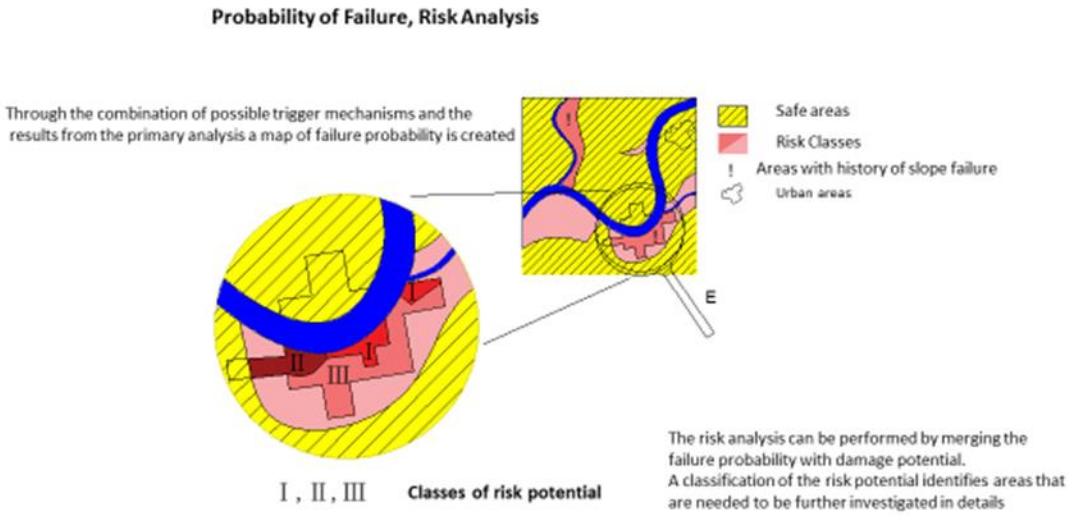


Figure 4 Classification of risk potential

2. Users and possible uses

Input data, metadata, basic information levels as well as the results of intersections and evaluations are stored in the form of a uniformly structured database in a specialist information system "Risk potential of landslides". In addition, the result can be processed and visualized in the form of a cartographic representation of the risk potential.

The process is designed so that not only an assessment of the current situation is possible, but also changes due to planning activities can be analyzed prior to implementation.

The rule-based derivation of the risk potential on the basis of an updatable database enables a dynamic view that allows a simulation of different scenarios. As a result, the analysis method is not only used to document or evaluate an "actual" state, but can also be fully integrated in the planning of anthropogenic interventions.

In addition, the fact that the combination of basic information levels with the database enables the immediate questions posed by users to be addressed in a differentiated manner makes the use of information flexible.

Accordingly, the presented evaluation method can be used, depending on the scale, at regional, but in particular also at local level. The provision of information in a database, together with the identification of priority areas with high risk potential and the specification of local parameters that need to be further integrated, enables a cost-effective approach to risk and damage reduction of landslides. The specification of the most likely failure mechanism enables the targeted use of adequate stabilization measures.

Thus, the evaluation process will also gain importance on the level of expert opinions regarding slope stability, since not only the area size to be examined is minimized, but the results of the evaluation process can be directly integrated into more extensive studies.

In addition to authorities and experts, the characterization of the risk potential also benefits all those who have to raise large sums annually to prevent landslides or to clean them up. In addition to insurance companies, these are primarily commercial companies, such as Deutsche Bahn AG (railway network), which is constantly confronted with the problem of unstable slopes due to its extensive, national infrastructure.

3. Conclusion

For a safe and sustainable development and infrastructure planning, basic information is required about the building site, the geological environment, areas with a high risk of landslides, etc. In this context and in order to meet the increasing demand for protection against natural disasters, in particular landslides - hazard maps are a valuable planning tool in decision-making and an important element in risk analysis with regard to mass movements. Due to their preventive nature, hazard maps or hazard warning cards are often a cost-effective element of sustainable disaster prevention, which is proven by many years of experience in Germany, Switzerland, and Austria.

Natural disasters are the result of a temporary coincidence of various geological, soil or rock mechanical, hydrological, climatological, anthropogenic factors, as well as their spatial distribution. Therefore, the identification of the causes, the detection of the failure mechanisms, the risk assessment and the choice of suitable countermeasures to reduce the risk are very complex and require an integrated approach.

This paper provides an overview of the traditional and modern methods of risk assessment for landslides. In addition, new technologies for data preparation, problems in connection with data acquisition and modeling as well as their implementation with regard to risk assessment are discussed. The presented step-wise approach to produce hazard and risk maps is feasible by combining GIS with expert knowledge and data mining methods.

The authors have presented a viable method that allows the integrated detection and evaluation for landslide hazard, based on spatial data and data mining technologies using GIS as visualization technology. This method considers the failure mechanisms combining different methods for assessment of landslide hazard and risk potential.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

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