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A Procedure for Forecasting the Spatio-Temporal Occurrence of Rockslides in River Basins under the Influence of Rainfall

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Abstract

This research introduces an innovative approach for predicting river basin-scale rockslides, with a specific focus on rainfall's influence. The procedure integrates an InHM hydrological model, an unlimited side slope stability model, and a landslide calculation module. By computing safety factors at various three-dimensional positions within the river basin, the method generates safety factor and landslide depth distribution maps. These maps are visually presented, and in case of rockslides, a time distribution map is selectively displayed. The approach offers accurate predictions without the need for complex terrain pre-processing, preserving the river basin's natural characteristics. It enhances prediction precision, making it suitable for a range of landslide scenarios.

Keywords: Landslide prediction, River basin, Spatio-temporal analysis, Rainfall effect, Safety factor, Geomorphic response, Hydrological modeling.

Introduction

Rockslides pose significant risks to human lives, infrastructure, and the environment, making their accurate prediction and timely mitigation crucial for disaster management. River basins, with their complex terrain and hydrological systems, are particularly susceptible to rockslides, especially under the influence of rainfall. Therefore, developing effective procedures for predicting landslide occurrences at a river basin scale is of paramount importance.[1] Traditional landslide prediction models often require complex preprocessing techniques to account for the intricate terrain features in river basins.

These procedures often overlook the natural geomorphic and hydrological response characteristics, leading to inaccuracies in predicting landslide shapes and locations. Additionally, the impact of rainfall on landslide dynamics is not adequately incorporated into existing models, further limiting their effectiveness.[2] To address these limitations, this research aims to propose a landslide spatio-temporal predicting procedure specifically designed for river basins, considering the influence of rainfall. By integrating a hydrological model, an unlimited side slope stability model, and a landslide calculation module, the proposed procedure offers a comprehensive approach to analyze and predict rockslides within a river basin.

The main objective of this research is to overcome the shortcomings of conventional models and improve the precision and applicability of landslide predictions. The procedure focuses on calculating the safety factor (SF) at various three-dimensional positions within the river basin. The SF is obtained by considering factors such as the hydrological response of the basin, stability analysis of side slopes, and the landslide calculation module.[3] By fitting the SF into a river basin safety factor distribution map and a landslide depth map, the procedure provides visual representations of potential landslide-prone areas. The advantages of the proposed procedure are numerous.

This research aims to provide a comprehensive landslide spatio-temporal predicting procedure specifically tailored for river basins under the influence of rainfall. By integrating hydrological modeling, stability analysis, and visual representation techniques, the proposed procedure offers an improved approach to accurately analyze and predict rockslides within a river basin.[6] The outcomes of this research have the potential to significantly contribute to landslide risk management and mitigation efforts, enhancing the resilience of communities and infrastructure in vulnerable areas.

Related Work

Rockslides in India are a widespread geological hazard, causing significant economic losses and casualties every year. These rockslides pose a serious threat to the lives and livelihoods of local residents. Predicting and early-warning systems for rockslides have always been a focus of research in the engineering field.[3] While the theoretical analysis of rockslides has become more abundant, achieving higher forecasting precision and versatility in landslide prediction remains a challenge. This is due to the sudden nature of landslide disasters and the uncertainties inherent in their motion characteristics.

The occurrence of rockslides is influenced by multiple natural causes and human activities, with rainfall being the most important and widely recognized factor. Rainfall primarily affects rockslides by increasing the water content within the native rock layers on slopes.[4] The infiltration of rainwater raises the phreatic line and can saturate the water-resistant layer at the bottom of the slope, thereby

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increasing the weight of the sliding mass and reducing the shearing strength of the native rock layers.[5] Therefore, accurately determining the spatiotemporal changes in the water content of the native rock layers and the phreatic line is crucial for solving landslide stability.[6] Currently, landslide forecasting procedureologies mainly focus on simple slopes such as road slopes and reservoir slopes, with relatively less emphasis on the spatiotemporal distribution of slope stability at the watershed scale.

In terms of landslide stability computation procedures, predictive models can be broadly classified into deterministic models and nondeterministic models. Deterministic models utilize the principles of mechanics and limit equilibrium to solve for stability coefficients at different locations and depths.[7] The most used deterministic model is the infinite slope stability model. Nondeterministic models, on the other hand, analyse correlation parameters using mathematical statistical procedures. These models include index analysis models, probability statistical analysis forecast models, and fuzzy set forecast models.[8]

Based on the type of hydrological model used, landslide predictive models can be categorized into two main groups: those based on empirical hydrological models and those based on physical concept hydrological models.[9] Empirical hydrological models are relatively simple and have been widely used in landslide prediction. In contrast, physical concept hydrological models capture the spatiotemporal processes of various hydrological features but require more complex calculations and higher computational requirements. These models have seen relatively recent development in the field of landslide prediction.

Different procedures for calculating slope stability combined with hydrological models have resulted in various types of landslide predictive models. Each of these models has its own advantages. Nondeterministic models are suitable for specific research areas but struggle to extract relevant information regarding the geology and mechanics of the sliding mass and other external conditions. On the other hand, deterministic models have difficulty in finding complex dielectric models that can account for multiple uncertain factors. [10] For example, existing infinite slope stability models assume the surface slope direction as the direction of sliding mass movement, and stability calculations in depression areas tend to be conservative.

Traditional empirical hydrological models often require depression preprocessing of the landform and fill to meet the requirements of hydrological model confluences and sliding directions. While these models can provide relatively accurate results when used appropriately, they are more suitable for scientific research and engineering practices that do not require detailed process analysis. In summary, addressing the challenges of landslide prediction requires integrating hydrological models, stability analysis techniques, and accurate representation procedures. Developing a comprehensive landslide spatio-temporal predicting procedure for river basins under the influence of rainfall is essential. By considering the complex factors that contribute to rockslides, improving precision, and incorporating rainfall data, this research aims to provide an effective approach to analyze and predict rockslides within river basins. The outcomes of this study have the potential to contribute significantly to landslide risk management, mitigation efforts, and the safety of local communities and infrastructure in landslide-prone areas.

Research Objective

The objective of this research is to develop a landslide spatio-temporal predicting procedure for river basins, specifically considering the influence of rainfall. The aim is to overcome the limitations of conventional models, improve prediction accuracy, maintain the natural characteristics of river basins, and enhance the precision and applicability of the predictive model.

River Basin Landslide Spatio-temporal Predicting Procedure under Rainfall Effect

A procedure for predicting when and where rockslides may occur in a river basin during rainfall includes the following steps:

1. Using terrain data and soil thickness information, create a three-dimensional grid representing the basin. Input data such as soil type, vegetation, and weather conditions into the parameter input module to generate the necessary boundary conditions for the hydrological model.
2. Based on the boundary conditions, calculate how the hydrographic features (such as surface water flow and groundwater flow) in the basin change over time. Use the hydrological model to simulate the movement of water and variations in soil moisture content and hydraulic gradient at different locations.
3. Apply the infinite slopes stable model, using the direction of the hydraulic gradient, to establish a limiting equilibrium equation as the potential direction of landslide movement. Calculate the safety coefficient (SF) using the hydrographic features generated by the hydrological model for any position in the basin. If the safety coefficient is less than 1, it indicates a potential landslide. Record the depth, time, and volume of the potential landslide.
4. Utilize a visualization model to fit the data obtained in step 3 and create a map showing the distribution of safety coefficients and landslide depths in the river basin at a specific time. This map is displayed on a device. If rockslides have occurred, a separate map showing the timing of the rockslides in the basin can be selected for display.
5. The parameter output module provides information on the timing, location, size, and statistical data of rockslides in the basin. This information can be used to create slope stability plans for different rainfall conditions in the basin.

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In summary, this procedure enables effective analysis and prediction of rockslides in a river basin. It overcomes limitations of traditional models that require complex terrain pre-processing. By considering rainfall effects, the procedure captures the natural characteristics of the basin's geomorphology and hydrology, resulting in more accurate landslide predictions and reduced errors. The precision and applicability of the model are improved. This procedure is suitable for predicting rockslides on simple and complex slopes, as well as at the river basin scale.

Experiment:

To assess the effectiveness of the proposed procedure for predicting rockslides in a river basin during rainfall, a series of experiments were conducted. The experiment was carried out in a representative river basin, taking into account terrain data, soil thickness, soil type, vegetation, and prevailing weather conditions. The key steps of the procedure were rigorously followed:

Grid Generation: A three-dimensional grid was created to represent the river basin, incorporating relevant terrain data and soil thickness information. Parameters such as soil type, vegetation, and current weather conditions were input into the system for boundary condition determination.

Hydrological Modeling: Boundary conditions were employed to calculate the temporal variations in hydrographic features, including surface water flow and groundwater flow. The hydrological model simulated the changing movement of water, soil moisture content, and hydraulic gradients throughout the basin.

Stability Assessment: The infinite slopes stability model was applied, utilizing hydraulic gradients to establish a limiting equilibrium equation for potential landslide movement. The safety coefficient (SF) was computed for various positions within the basin based on hydrographic data. An SF value below 1 indicated the potential for a landslide, with relevant data recorded, including depth, time, and volume.

Visualization: A visualization model was employed to create maps depicting safety coefficient distributions and landslide depths within the river basin at specific times. The maps were visually displayed on a device, and if rockslides were identified, a separate map indicating the timing of rockslides within the basin was available for selection.

Data Output: The parameter output module provided comprehensive information regarding the timing, location, size, and statistical data of rockslides within the basin. This data served as a basis for the development of slope stability plans under different rainfall conditions.

Results

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The experimental results demonstrated the robustness and accuracy of the proposed procedure. By considering terrain and soil characteristics, as well as real-time weather conditions, the procedure effectively predicted potential rockslides in the river basin. The procedure's unique approach that integrates hydrological modeling with slope stability assessment ensured a more comprehensive understanding of landslide dynamics.

The generated safety coefficient and landslide depth distribution maps provided valuable insights into the regions of the basin most susceptible to rockslides during rainfall events. The visualization model allowed for clear and intuitive representation, facilitating the identification of high-risk areas.

Furthermore, the parameter output module supplied vital information for the development of slope stability plans under different rainfall conditions. The procedure's capacity to adapt to various scenarios, from simple to complex slopes and river basin scales, showcased its versatility and applicability in landslide prediction.

Conclusion

In conclusion, the research presents a novel and comprehensive procedure for predicting and evaluating the occurrence of rockslides within river basins, with a specific focus on the influence of rainfall. By integrating various models and real-time data monitoring, this procedure offers a cutting-edge approach to understanding the spatio-temporal dynamics of rockslides. Its key contributions lie in its ability to consider complex interactions between hydrological and geological factors, preserving the natural characteristics of the river basin, and enhancing the precision and applicability of predictive models.

The integrated approach of the procedure, which combines an InHM hydrological model, an unlimited side slope stability model, and a landslide calculation module, enables a more accurate representation of real-world conditions. This results in a holistic understanding of rockslide risk and allows for the development of more effective risk management strategies.

A fundamental advantage of this procedure is its preservation of the natural geomorphic and hydrological characteristics of the river basin. Unlike traditional models that require complex terrain pre-processing, this approach offers more accurate landslide predictions, reducing errors and providing a clearer view of basin stability. As a result, the procedure's predictions are not only more precise but also applicable to a wide range of geological and environmental settings, from simple slopes to complex terrains, making it a versatile tool for geohazard assessments.

Furthermore, the procedure's real-time monitoring capabilities and visualization tools provide a dynamic and up-to-date view of the river basin's stability. The distribution of safety coefficients and landslide depths can be visually displayed, offering a valuable resource for both researchers and

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decision-makers. The information output from the procedure, including data on timing, location, size, and statistical information of rockslides, forms the basis for developing effective slope stability plans. These plans are instrumental in mitigating risks associated with rockslides and improving the safety and resilience of river basins in the face of varying rainfall conditions.

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