Review on Forecasting of Mass Shallow Landslides and Debris Flows

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Abstract: As a highly destructive natural disaster, the accurate prediction of clustered shallow landslide-debris flow hazards is of great significance for ensuring the safety of people's lives and property and reducing economic losses. In recent years, with the continuous advancement of science and technology, significant progress has been made in the research of forecasting models for clustered shallow landslides and debris flows. Scholars have conducted in-depth studies from multiple perspectives, including the formation mechanisms of landslide-debris flow disaster chains, numerical simulation methods, artificial intelligence prediction technologies, and the integrated application of multi-source monitoring and early warning systems. This paper systematically reviews and summarizes the current research status in the above fields, identifies key future research directions for landslide-debris flow disaster forecasting, and provides a theoretical foundation and technical support for developing more accurate and efficient forecasting systems.

Keywords: Cluster Occurrence; Landslide-Debris Flow; Forecast

1. Introduction

In recent years, the increasing frequency and intensity of cascading geological disasters—particularly the landslide-debris flow-river blockage-outburst flood chain—have drawn significant scientific and societal attention. Driven by factors including seismic activity, global climate change, and expanded human engineering operations, such multi-hazard sequences have become representative regional disaster processes in many mountainous areas worldwide.

A striking example occurred in December 2023, when a major earthquake struck Jishishan County in Gansu Province, China. The seismic shocks triggered an extensive series of slope failures, registering 4,996 individual landslides within an affected area of 725 km². These landslides rapidly mobilized into large-scale mudflows, which inundated vast valley zones and buried multiple villages, as visually documented in Fig. 1(a).

Similarly, in April 2024, persistent extreme rainfall in Guangdong Province induced widespread shallow landslides across an 89 km² region in Jiangwan Town, Shaoguan. As depicted in Fig. 1(b), these slope failures supplied immense volumes of sediment and debris. Propelled by high kinetic energy and augmented by substantial runoff, the material converged into river channels, causing extensive blockages and a rapid rise in water levels. This process culminated in severe flooding across Jiangwan Town, exacerbating the disaster impact.

These cases underscore a growing pattern: mountain disaster chains that integrate landslides, debris flows, and subsequent flooding are becoming increasingly common. Such chains exhibit non-linear impact amplification, where initial triggers lead to disproportionately severe outcomes. This complexity introduces substantial challenges for hazard assessment, predictive modeling, and emergency management.

A critical scientific challenge lies in the incomplete understanding of the mechanisms governing the transition from clustered shallow landslides to debris flows. The high stochasticity of rainfall and the abrupt onset of such landslides often preclude early detection and preventive intervention. When these slope failures evolve into debris flows, the potential for large-scale human casualty and infrastructural damage rises dramatically.

Thus, a systematic review of current research on the transition mechanisms of clustered shallow landslides to debris flows is urgently needed. Establishing a clear mechanistic framework is essential for improving predictive capacity and developing effective early warning systems. In light of evolving research trends, this analysis focuses on three prominent themes: (1) Fully coupled numerical modeling of the entire landslide–debris flow disaster chain; (2) Artificial intelligence-based predictive frameworks for landslide and debris flow hazards; (3) Integrated real-time monitoring and early warning platforms that leverage multi-source data for dynamic disaster tracking. Advancements in these domains are crucial for mitigating risks associated with compound and cascading geological hazards in vulnerable regions globally.

(a) (b)

Figure 1. (a) The Area Affected by Landslide-Mudflow Disasters in Zhongchuan Township, Qinghai Province; (b) Satellite Remote Sensing Map of the Sentinel 2 Area of the Clustered Landslides in Jiangwan Town

2. Coupled Simulation of the Entire Process of Landslide-Mudslide Disaster Chain Based on Numerical Models

Full-process coupling simulation of disaster chains serves as a core technology for deeply understanding and accurately predicting complex geological hazards. It encompasses the entire sequence of disaster stages—from the initial occurrence and progressive evolution of landslides, to the eventual triggering of debris flows, followed by their subsequent movement and deposition. In this process, numerical models play an indispensable role: they not only simulate the formation mechanisms of such disaster chains but also reveal their kinematic characteristics, thereby providing a scientific basis for hazard assessment. Through such simulations, researchers can gain a more comprehensive understanding of the dynamic processes of disaster chains, offering robust technical support for disaster prevention and mitigation efforts.

(1) Formation and characteristics of the disaster chain

The landslide-debris flow disaster chain is often triggered by external factors such as extreme rainfall or earthquakes. For example, the 2008 Wenchuan earthquake initiated numerous landslides, and on July 10, 2013, a major landslide-debris flow disaster struck the Dujiangyan area, resulting in 166 fatalities. As the landslide mass moves, it can mix with water, forming a viscous, high-concentration solid-fluid mixture known as debris flow [1]. This type of disaster chain is characterized by its sudden onset, short duration, and high destructiveness, causing significant damage to infrastructure such as houses, bridges, farmland, and roads, and posing a serious threat to people's lives and property. In the high-altitude regions of the Qinghai-Tibet Plateau, landslide dams are key components of the watershed geological disaster chain, and their failure modes are primarily influenced by the anisotropy of geotechnical materials. In some cases, landslides can also block rivers, leading to the formation of barrier lakes. The breach of these barrier lakes can, in turn, trigger more severe floods and debris flow disasters (as shown in Fig.2). For instance, following the substantial damage caused by a debris flow in Atami City, Shizuoka Prefecture, new regulations in Japan have standardized the construction of earth embankments, emphasizing the risk assessment of landslides potentially blocking river channels during seismic events and thereby inducing floods and debris flows [2].

(2) Numerical simulation development

To accurately predict and assess the landslide-debris flow disaster chain, numerous scholars have developed various numerical simulation methods. These approaches typically require knowledge spanning multiple disciplines, including geomechanics, fluid dynamics, and material mechanics.

Debris flows possess properties of both solids and liquids, exhibiting shear resistance similar to soil and the ability to flow like a fluid. Most existing dynamic models for debris flows are derived from hydraulic or geotechnical engineering models. Consequently, they can be classified into continuous medium, discrete medium, and hybrid medium models based on their constitutive principles and motion descriptions[3]. Regarding the Finite Element Method (FEM) and the Discrete Element Method (DEM), these methods are now widely used to simulate the dynamic processes of landslides and debris flows. Zhou et al. combined the FDM and DEM methods to simulate the initiation and deposition processes of large-scale seismic landslides and debris flows[4]. Wang et al. utilized a PFC sphere model to represent the landslide mass and a wall model to represent the sliding bed, analyzing the sliding process and deposition characteristics of the landslide by applying seismic wave loads[5].

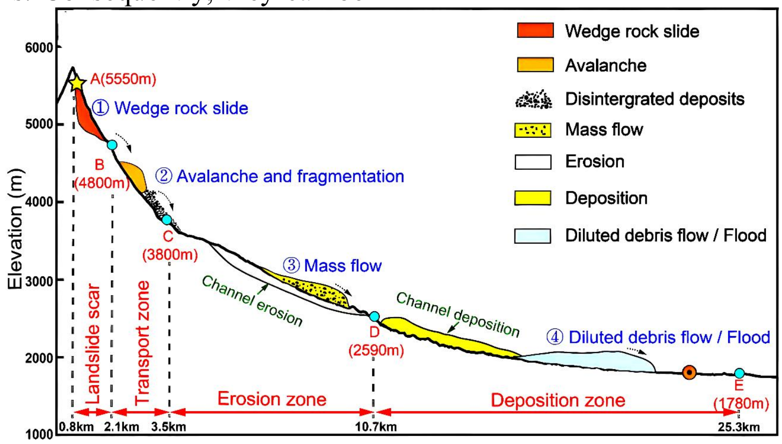

Figure 2. Diagram of the Conversion Process between Landslides and Mudflows

In the area of Smoothed Particle Hydrodynamics (SPH), Zhu et al. applied a coupled SPH-DEM approach to study the breach process of landslide dams formed by earthquake-induced landslides[6]. Zhang et al. used an SPH model to simulate the interaction between an actual landslide and a rigid barrier, aiming to assess the landslide's travel distance and impact force[7].

3. Model Prediction of Landslide and Debris Flow Disasters Based on Artificial Intelligence Technology

AI-based prediction of landslide and debris flow hazards represents a significant research direction in the interdisciplinary field of Earth sciences and artificial intelligence. It aims to utilize advanced algorithms and models to enhance the accuracy and timeliness of disaster warnings, thereby effectively mitigating the impacts on human lives, property, and socio-economic development. Traditional methods for geological hazard prediction, such as mathematical statistics and physical models, exhibit limitations in addressing low-probability events and complex nonlinear characteristics. In contrast, artificial intelligence technologies, particularly machine learning and deep learning, have introduced new breakthroughs in landslide and debris flow hazard prediction due to their robust data processing capabilities and pattern recognition abilities.

AI finds one of its most extensive applications in landslide susceptibility assessment and mapping. Scholars use AI models to analyze various triggering factors such as geology, topography, hydrology, and meteorology to generate regional landslide susceptibility maps. Commonly used machine learning methods include Random Forest, Support Vector Machines (SVM), Artificial Neural Networks (ANN), and Decision Trees. Among these, the Random Forest model has proven effective in improving prediction accuracy due to its capability to handle complex nonlinear relationships[8]. Liu proposed a method combining K-means and KNN algorithms to optimize negative sample selection, thereby enhancing the accuracy of machine learning models in landslide susceptibility assessment[9].

For landslides that have already occurred but are still deforming slowly, accurate prediction of their future displacement is crucial for early warning. An Extreme Learning Machine (ELM) model combined with the Grey Wolf Optimizer (GWO) algorithm, known as the GWO-ELM model, has been used to predict the displacement of the Caojiatuo landslide in the Three Gorges Reservoir area, achieving favorable results [10].

Accurate prediction of the peak discharge of debris flows is critically important for early warning systems. Research has proposed hybrid intelligent models that use AI technology to compensate for the shortcomings of traditional hydrological models, such as HEC-HMS, in simulating the effects of sediment concentration, for predicting debris flow peak discharge [11].

Integrating artificial intelligence with the Internet of Things (IoT) and hydraulic models enables the construction of real-time monitoring and dynamic numerical prediction systems for floods and landslide disasters. Such systems can provide more efficient disaster monitoring and early warning support, contributing to disaster prevention and management [12].

4. Real-Time Tracking Technology for Landslides and Debris Flows based on the Integration of Multi-Source Monitoring and Early Warning Technologies

Of growing importance in geohazard risk reduction, the real-time tracking technology for landslides and debris flows represents a paradigm shift in disaster management. By systematically integrating multi-source monitoring networks—including ground-based sensors, satellite remote sensing, and unmanned aerial systems—with advanced early warning platforms, this approach enables comprehensive dynamic monitoring of slope instability and debris flow initiation processes. Through sophisticated data fusion algorithms and machine learning techniques, the system continuously analyzes heterogeneous datasets in near-real-time, facilitating accurate risk assessment and generating timely alerts with improved lead times. This integrated framework not only enhances situational awareness for emergency responders but also enables proactive evacuation planning and infrastructure protection, thereby significantly reducing potential casualties and economic losses. Furthermore, the technology supports long-term disaster resilience by building historical databases for pattern recognition and model refinement, ultimately contributing to more sustainable development in geologically hazardous regions. The implementation of such systems in high-risk areas like the Sichuan basin and Three Gorges region has demonstrated practical effectiveness in mitigating disaster impacts through science-informed decision support.

4.1 Development of Multi-Source Monitoring Technology

Real-time tracking of landslides and debris flows relies on the integrated application of multiple monitoring technologies, which capture precursor information of disasters from different dimensions: ground-based monitoring systems such as fiber optic sensing technology, Global Navigation Satellite Systems, Micro-Electromechanical Systems, Acoustic Emission technology[13], tilt sensors, microseismic monitoring, and Internet of Things technology[14]; and remote sensing monitoring systems such as satellite/airborne remote sensing[15], ground-based synthetic aperture radar, Interferometric Synthetic Aperture Radar, and unmanned aerial vehicles [16].

4.2 Real-Time Early Warning and Management Technology Development

Real-time early warning and management technologies are critical components in the prevention and control of landslide and debris flow disasters. With the rapid advancement of information technology, modern early warning systems are now capable of integrating multi-source monitoring data. Through efficient data processing and analytical algorithms, these systems enable rapid risk assessment and timely dissemination of warnings. They are characterized by a high degree of automation and intelligence, and can dynamically adjust warning thresholds based on real-time monitoring data, thereby improving both the accuracy and timeliness of alerts. Furthermore, by integrating Geographic Information Systems and remote sensing technologies, these systems can visually display the location, extent, and potential impact pathways of disasters, providing robust support for emergency response and rescue operations.

Key research in this area includes: Wang et al. proposed a graded early warning mechanism based on landslide mechanics and dynamic monitoring data[17]. This approach utilizes a self-adaptive analytic hierarchy process and fuzzy comprehensive evaluation to establish a hierarchical structure and quantitative thresholds, enabling early landslide warnings driven by multi-source dynamic data. Zhang et al. developed a monitoring and early warning system for geological disasters based on big data analytics, aiming to address the issues of significant monitoring errors and low accuracy in existing systems[18]. Hui et al. achieved successful warnings for two landslide events in a demonstration mining area by developing high-precision microseismic positioning technology, creating high constant-resistance and large-deformation energy-absorbing anchor cable monitoring devices, and establishing a multi-source information fusion early warning evaluation model[19]. This technology offers new insights for the safety monitoring and control of high-steep slopes. Additionally, Nie et al. developed a multi-source intelligent monitoring and early warning system that integrates information from physical model tests, 3D reconstruction, numerical simulations, and field monitoring[20]. This system enables visualization and intelligent prediction of rainfall-induced landslide scenarios.

5. Conclusion

In summary, significant progress has been made in recent years in the research of forecasting models for clustered shallow landslides and debris flows. The fully coupled numerical simulation of the entire landslide-debris flow disaster chain has enabled in-depth analysis of its formation processes and characteristics, driving advancements in numerical modeling and providing a powerful tool for understanding disaster mechanisms. AI-based predictive modeling for landslide and debris flow hazards utilizes advanced algorithms to enhance prediction accuracy and timeliness. Meanwhile, real-time tracking technology integrating multi-source monitoring and early warning systems has achieved visualization and intelligent prediction of disaster scenarios by synthesizing diverse information, offering new approaches for safety monitoring and control in areas such as high-steep slopes.

However, despite the considerable achievements in the research of forecasting models for clustered shallow landslides and debris flows, several challenges and limitations remain. For instance, the formation conditions of landslides and debris flows vary significantly across different regions, and the general applicability of existing numerical and AI-based predictive models still requires improvement to fully adapt to diverse complex geological environments and climatic conditions. Furthermore, although the integration of multi-source monitoring and early warning technologies has enabled visualization and intelligent prediction of disaster scenarios, there is still room for enhancement in terms of data real-time performance and accuracy. How to more precisely capture early signals of disaster initiation and further improve the reliability of early warnings represents a critical direction for future research.

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