A Review of Earthquake Landslide Hazard Assessment Methods

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ABSTRACT

Landslides triggered by earthquakes are large in scale and wide in scope, making them one of the most serious geological disasters. Earthquake landslide hazard assessment has become an important part of disaster reduction and prevention work. Based on existing research and assessment practices, such an assessment is divided into two levels: individual landslide assessment and regional landslide assessment. The individual assessment, mainly required by specific engineering seismic issues, serves as the foundation of earthquake landslide hazard assessment. It includes two analysis methods: qualitative analysis based on causal relationships (e.g., comprehensive indicator modeling, logistic regression, neural network modeling, information quantity evaluation) and mechanical analysis based on physical-mechanical mechanisms (e.g., quasi-static method, Newmark method, dynamic time-history method). This paper summarizes the characteristics and problems of these two methods. Regional assessment caters to regional strong earthquake geological disaster rescue deployment, future earthquake defense planning, and engineering construction strategic layout. It has two strategies—"from region to individual" (earthquake-focused, coarse-to-fine) and "from individual to region" (landslide-focused, point-to-area)—which differ in observation angles and technical routes. Currently, the individual assessment can estimate landslide hazard probability by considering potential seismic source ori-entations, but the regional assessment lags, e.g., ignoring such orientations and lacking the application of the dynamic time-history method. Thus, this paper proposes establishing slope seismic resistance fields and multi-azimuth seismic impact fields, then overlaying them to determine regional earth-quake landslide distribution probability, and points out future research directions.

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1 Introduction

The earthquake is one of the most serious natural disasters. Strong earthquake destroys buildings and induces secondary geological disasters, which bring harm to human beings. Earthquake-induced landslides are large in scale and wide in scope, and are one of the most serious geological disasters [1–3]. For example, the 5.12 Wenchuan Earthquake triggered nearly 200,000 (197,481) landslides in an

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area of 110,000 km^2. The landslides buried houses, destroyed buildings, blocked rivers, and caused a large number of casualties and huge property losses [4–8]. The earthquake-induced landslide disasters are shocking and frightening. So, the analysis and prediction of the earthquake slope stability have become a major task in geotechnical engineering and earthquake engineering [9–11].

In a certain future period, what is the probability of slope instability in some kind of modes caused by earthquake? This is a basic scientific question that needs to be answered for the slope earthquake hazard assessment (i.e., the earthquake landslide hazard is equivalent to the possibility of slope instability caused by earthquake). This issue involves two aspects: One is the possibility of the slope being subjected to some form of seismic actions in a certain period in the future (site seismic hazard) [12,13]; The other is the mode and possibility of slope instability caused by such seismic loads [14–16]. This issue can be divided into **two levels**: **individual earthquake landslide hazard** and **regional earthquake landslide hazard**.

The individual earthquake landslide hazard assessment has a guiding significance for the earthquake fortification of a specific project. This is one of the concrete embodiments of the engineering application value for the research on the seismic instability of slopes. In addition, the individual earthquake landslide hazard is the basis of earthquake landslide hazard research (including regional earthquake landslide hazard assessment), and it is of vital scientific significance to understand the physical and mechanical process of an earthquake landslide deeply, consider the uncertainty of seismic action and seismic slope instability comprehensively, estimate the probability of seismic slope instability, and form earthquake landslide hazard assessment methods. The research on the seismic stability and earthquake hazard of individual slope has been a concern for a long time and reached a relatively high level both in engineering application and scientific study, so that a relatively mature analysis method of earthquake landslide hazard considering the orientation of potential seismic sources and the uncertainty of seismic actions has been formed [12,13,17,18].

The regional earthquake landslide hazard assessment is of great strategic significance for future earthquake disaster prevention planning and construction layout in a certain area. For the large-scale, widely distributed, and seriously destructive earthquake landslide disasters, it is far from enough to pay attention only to the seismic stability of individual slopes. Thus, regional earthquake landslide hazard assessment must be carried out to provide effective support for regional defense planning of earthquake landslide disasters. From the perspective of scientific research, regional earthquake landslide hazard involves more factors, such as earthquake-influence fields generated by different seismic sources, spatial variation and superposition of regional engineering geological conditions, etc. It is an important topic in the study of Earth's surface dynamics, and there are more challenging problems worthy of further study. Compared with the study of individual earthquake landslide hazards, the study of regional earthquake landslide hazards started relatively late. Due to the impact of large-scale regional earthquake landslides on social security and the economy in recent years, the strategic need for the prevention of regional earthquake landslides in the future has become urgent, and regional earthquake landslide hazard has gradually become a hot issue in the research of earthquake geological disasters.

In this paper, we provide **an overview focused on the hazard assessment method of regional earthquake landslides in a certain future period**. This is done by considering our most recent experiences, as well as published studies by others. We first examine the individual earthquake landslide hazard assessment method and the regional earthquake landslide hazard assessment method. Then, we discuss the characteristics and problems of qualitative analysis and mechanical analysis methods. Lastly, based on the natural process of earthquake landslide disaster, the future research directions have been put forwards.

2 Research Status at Home and Abroad

Due to the threat of seismic slope disasters to human beings, earthquake-induced landslides have been concerned more and more. Many scholars in related fields have carried out multi-disciplinary and multi-level research on the seismic landslide disasters. From seismic stability analysis of individual slopes to regional earthquake landslide hazard assessment, from causal qualitative assessment of earthquake landslide hazard to mechanical analysis of seismic slope stability, human beings have made unremitting efforts to mitigate the seismic slope disasters.

2.1 Individual Earthquake Landslide Hazard Assessment

The individual earthquake landslide hazard (seismic slope stability) is the first concern of engineering, and it is also the basis of earthquake landslide hazard assessment. The corresponding research work was started relatively early. As shown in Fig. 1, for individual earthquake landslide hazard analysis, there are two categories of assessment methods [19]: One is the qualitative assessment of earthquake landslide hazards based on causal relationships; The other is the mechanical analysis of earthquake landslide hazards based on physical and mechanical mechanisms.

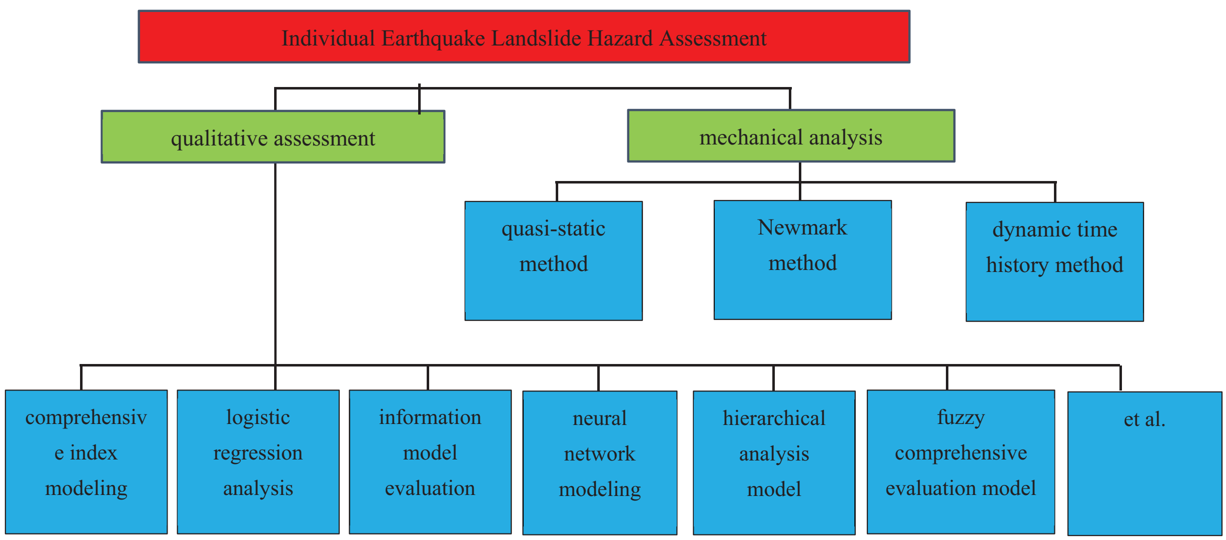

Figure 1: Individual earthquake landslide hazard assessment method

(1) Qualitative assessment methods

Qualitative analysis of earthquake landslide hazards considers the possibility of slope seismic instability from the perspective of disaster system composition.

The hazard-causing body (slope rock and soil mass) and the hazard-affected body (human lives and property) are two fundamental physical components of a disaster system. Triggered by specific inducing factors—such as seismic dynamic effects—the hazard-causing body initiates a disaster process (e.g., a landslide) of a certain intensity. During this process, if the hazard-causing body comes into contact with the hazard-affected body, it may result in disaster consequences of varying severity, including building damage, and loss of life and property. Hazard refers to the probability that the hazard-causing body would undergo a disaster process of a specific intensity. Disaster risk, by contrast, denotes the probability of consequences from the interaction of the hazard-causing body and the hazard-affected body. Susceptibility of the hazard-causing body describes the ease or difficulty with which a disaster process can be initiated. Vulnerability of the hazard-affected body, on the other hand, refers to the likelihood of the body sustaining damage (or losses) of a certain degree when exposed to the disaster process—or, alternatively, the sensitivity of the hazard-affected body to the disaster process.

Taking seismic dynamic loads acting on slope masses as the cause and landslide occurrence as the result, the qualitative analysis of earthquake-induced landslide hazard focuses on the possibility of landslide initiation (i.e., the occurrence of the disaster process) driven by seismic dynamics (as the inducing factor) from a causal perspective. First, **parameters characterizing landslide susceptibility** (i.e., slope stability) were selected, including: (1) slope attribute parameters (e.g., slope topography, formation lithology, and geological structure parameters); (2) geological environment parameters (e.g., regional tectonic activity in the area where the slope is located, and the distance from the slope to major faults); and (3) geographical and climatic parameters (e.g., temperature, humidity and their variations, rainfall conditions, and the influence of surface and groundwater on the slope). Second, **parameters describing landslide-inducing actions** were chosen, such as: (1) seismic dynamic parameters [including parameters representing the intensity of on-site seismic impacts (e.g., site intensity, peak ground acceleration, and Arias intensity) and parameters reflecting the level of seismic energy release or the scope of earthquake influence (e.g., earthquake magnitude and epicentral distance)]; and (2) rainfall parameters (e.g., cumulative rainfall, rainfall duration, and rainfall intensity). These parameters characterizing landslide susceptibility and describing landslide-inducing actions were collectively defined as "earthquake-induced landslide factors" to characterize the causes of earthquake-induced landslides.

Subsequently, representative historical earthquake-induced landslide events were selected. By comparing the value ranges of the aforementioned earthquake-induced landslide factors with the corresponding slope stability levels in these historical events, statistical criteria for earthquake-induced landslide hazard of the earthquake-induced landslide factors were established. These established statistical criteria reflect the causal relationship between earthquake-induced landslide factors and the occurrence of earthquake-induced landslides, and can be applied to future earthquake-induced landslide hazard assessments. Specifically, for a given slope, its earthquake-induced landslide factors can be obtained through geological surveys, and accordingly the earthquake-induced landslide hazard of the slope in a specific period in the future can be evaluated.

There are many ways to implement the ideas of earthquake landslide hazard assessment based on causality relationships as shown in Fig. 1, such as comprehensive index modeling, logistic regression analysis, neural network modeling, information model evaluation, hierarchical analysis model, and fuzzy comprehensive evaluation model. The qualitative assessment of earthquake landslide hazards based on the disaster system framework and causality relationship needs deep understanding of the physical mechanism of earthquake landslides and strong supporting with a lot of data from actual earthquake landslides. Many scholars have contributed to the development of qualitative assessment methods of earthquake landslide hazards, such as: Keefer's (1984) [20] discussion of earthquake landslides and engineering geological analysis about seismic stability of slopes by Tsompanakis et al. (2010) [21]; and research work on earthquake landslide evaluation of rock and soil slopes by Ding et al. (2000) [22–24], Al-Homoud and Tahtamoni (2000) [25], Alalade et al. (2025) [26], Waris et al. (2025) [27]. As well as a series of research work on Wenchuan earthquake-induced landslide in 2008 by [28,29].

Guided by the disaster theory and supported by a large number of earthquake damage examples, the qualitative assessment of earthquake landslide hazards is relatively convenient and fast, so it can enable rapid assessment of regional earthquake landslide hazards in large range [30–34], which can provide not only timely basis for the deployment of earthquake relief and disaster reduction work, but also references for further research on the mechanical stability of earthquake landslides. Therefore, qualitative assessment of earthquake landslide hazards is a basic work of earthquake landslide disaster assessment. However, qualitative analysis alone of earthquake-induced landslides cannot meet the requirements for formulating detailed seismic design schemes for slopes and disaster mitigation measures. Therefore, mechanical analysis of seismic slope stability—grounded in the physical and mechanical mechanisms underlying earthquake-induced landslides—is also an indispensable component of related research.

(2) Mechanical analysis methods

The physical and mechanical mechanisms of earthquake landslides and the engineering geological properties of slopes as well as the characteristics of seismic actions are considered in mechanical analysis of individual earthquake landslide hazard. The mechanical analysis methods of seismic slope stability mainly include the quasi-static method, Newmark method, and dynamic time history method. So far, the analysis of individual earthquake landslide hazard has reached the level of estimating the probability of earthquake landslide hazard by considering the influence of the potential seismic source orientations [13,18,35].

The quasi-static method is the earliest single-slope seismic stability analysis method proposed in response to the basic need in engineering to understand the resistance limit of slopes to seismic action (the maximum seismic force that the slope can withstand) [36,37]. This method treats the sliding mass of a slope as a rigid body, and simplifies the seismic force acting on the sliding body as a static force (seismic inertia force) that drives slope instability.

In this framework, the sliding force along the direction of the potential sliding surface is formed by superimposing the seismic inertia force and the self-weight of the sliding mass. This sliding force together with the anti-sliding force on the potential sliding surface of the slope constitutes the force system acting on the sliding mass. Furthermore, by referencing the limit equilibrium method for static slope stability analysis, the maximum seismic force a slope can withstand is determined based on the static balance between the anti-sliding force and the sliding force.

The quasi-static method is not only the earliest but also the most widely adopted slope seismic stability analysis method in relevant engineering codes. For instance, the 1954 Code of Construction in Seismic Zones of the former Soviet Union [38] incorporated this method, as have China's seismic design codes for industries including construction, water conservancy, highways, and railways—all of which designate the quasi-static method as the basic approach for verifying slope seismic design [39–43].

The Newmark method was originally proposed as a method for slope stability analysis of hydraulic dams affected by earthquakes [44], and then it was promoted and developed in the seismic stability analysis of natural slopes [45–47]. Further considering the action characteristics of seismic dynamic, Newmark method determines the ultimate seismic resistance of a slope (the critical ground motion acceleration a_c of the slope site) using the quasi-static method first; then integrates the waveform $[a(t) \mid a(t) \geq a_c]$ against time t twice, in which, $a(t)$ is the whole-time history of ground motion acceleration acting on the slope, and $[a(t) \mid a(t) \geq a_c]$ is the seismic acceleration process that pushes the sliding body downward, so as to obtain the so-called Newmark cumulative displacement $D(t)$ of the slope. At last, in the light of the criterion $D(t) \geq D_s$, in which D_s is the critical value of Newmark cumulative displacement set for landslide initiation, the probability of seismic landslide hazard is derived from the exceeding probability of ground motion intensity at the slope site (e.g., the exceeding probability of the site ground motion acceleration $P\,[|a(t)| \geq a_c]$).

The application of the **dynamic time-history method** in the field of civil engineering originated from the seismic response analysis of structural engineering [48], and was subsequently extended to the seismic stability analysis of hydraulic dams [49–53]. Later, the severe impacts of strong earthquake-induced landslides on social security and economic development further promoted the extension and application of this method to the study of seismic stability of natural slopes [54–58].

Considering the dynamic properties of slope rock and soil masses, the dynamic time-history method focuses on analyzing the dynamic response of slopes throughout the entire process of seismic dynamic action (i.e., the dynamic time history). It reveals the influences of the three core elements of seismic dynamic action—dynamic intensity, frequency components, and duration—on slope seismic stability by investigating the dynamic responses of slope media to seismic actions of varying intensities (e.g., slope vibration time histories and dynamic stress time histories).

Based on the slope dynamic responses obtained via the dynamic time-history method, key dynamic characteristics of slopes can be identified, including: (1) resonance characteristics (associated with the frequency components of seismic actions and the physical-mechanical properties of slope masses); and (2) fatigue characteristics (related to the frequency components and duration of seismic actions, as well as the physical-mechanical properties of slope masses). Additionally, critical dynamic characteristic parameters can be derived, such as the dominant vibration mode (i.e., dominant frequency) and seismic resistance capacity (e.g., critical ground motion acceleration). Thus, the dynamic time-history method can provide a more comprehensive and detailed dynamic basis for the seismic design of slopes.

From the perspective of the implementation means of research methods, the quasi-static method, the Newmark method, and the dynamic time history method for seismic stability analysis of the individual slope can all be realized by physical simulation (physical model experiment) and numerical simulation (numerical model simulation). In terms of workload and complexity of research methods, the quasi-static method is the simplest, the dynamic time history method is the most complicated, and the Newmark method is in between, as shown in Table 1. With the progress of science and technology, the means of physical simulation and numerical simulation have made great progress, and the feasibility of the dynamic time history method has been greatly improved. Especially, with the rapid progress of computer technology and the in-depth study of related technical for the research methods (for example, the latest progress of technical methods for the excitation of oblique incidence seismic wave [18,59–64], numerical simulation method has become the main means for the implementation of dynamic time history method supplemented by physical simulation.

Table 1: Comparison of earthquake landslide mechanical analysis methods

Mechanical analysis methods	Workload	Complexity
Quasi-static method	Small	Simple
Newmark method	Middle	Middle
Dynamic time history method	Big	Complicated

2.2 *Regional Earthquake Landslide Hazard Assessment*

The demand fields on regional earthquake landslide hazard assessment are mainly the deployment of rescue work of strong earthquake geological disasters in a certain region, as well as the defense planning and engineering construction strategy layout for future earthquake disasters. Therefore, regional assessment is an essential component of earthquake-induced landslide hazard assessment, and has garnered significant attention and exploration from scholars in related fields.

Two main strategies are employed for regional earthquake-induced landslide hazard assessment. The first follows a "**region-to-individual**" approach: it starts with evaluating the likelihood of earthquake-induced landslides across a large-scale area, then proceeds to conduct seismic stability analysis on individual slopes, ultimately completing the hazard assessment for the entire region. The second adopts an "**individual-to-region**" approach: it begins with analyzing the seismic stability of individual slopes one by one in a region, and finally integrates these results to form a comprehensive understanding of the spatial distribution of earthquake-induced landslide hazard in the whole region.

Regardless of the strategy chosen, regional earthquake-induced landslide hazard assessment must be based on a thorough understanding of the engineering geological conditions of individual slopes and the physical-mechanical mechanisms governing their seismic stability, while also relying on substantial actual earthquake-induced landslide data for support.

Ding et al. (1997–2004) [22–24], referring to the three-level prediction method of earthquake landslides proposed by the Geotechnical Earthquake Engineering Committee of the International Association of Soil Mechanics and Foundation Engineering (IASMFE) in 1993, based on the study of recorded historical earthquake landslides in China, proposed an assessment and prediction implementation method of earthquake landslides which can be adapted to the characteristics of China's seismicity, and basically reflects the characteristics of the assessment strategy from region to individual of earthquake landslide hazard. The method assesses the slide and collapse of slopes triggered by earthquakes with three steps [24]: first, preliminarily delineating the possible range of collapses or landslides triggered by earthquakes with consideration mainly on the influence of earthquakes; then classifying the levels of slope failure possibility during earthquakes in the region delineated according to the causal relationship between slope seismic failures and slope properties; and finally conducting seismic stability analysis on the slopes with the highest probability of occurring earthquake-induced landslide. This assessment methods can efficiently identify the disaster-causing bodies of earthquake landslides, and it is more suitable for the needs of rapid assessment of earthquake landslide disasters in emergency and disaster relief work when large earthquakes occur.

Many scholars, for instance, Miles and Ho (1999) [65], Miles and Keefer (2009) [66], Nandi and Shakoor (2008) [67], Yilmaz (2009) [68], Djukem et al. (2025) [69], Li et al. (2019) [70], Sun et al. (2023) [31], Zhao et al. (2022) [71], have all carried out regional earthquake landslide hazard assessment works by the assessment strategy from individual to region. Some of the analysis methods used in these assessment works are qualitative assessment based on causal relationships (analytic hierarchical fuzzy comprehensive evaluation, comprehensive index modeling, information volume model analysis, etc.), and others belong to mechanical analysis based on physical and mechanical mechanisms (Newmark method). The spatial distribution of earthquake landslide hazards in the study area is formed from point to area, that is, studying the seismic stabilities of grids, which are equivalent to individual slopes and cover the study area with a certain spatial density, one by one, and forming slope seismic stability distribution of the area at last.

The fundamental difference between the two assessment strategies, the "region-to-individual" and "individual-to-region" approaches, lies in their distinct perspectives on observing earthquake-induced landslide events: The "region-to-individual" strategy centers on earthquake events, paying special attention on the impacts of earthquakes on slopes; in contrast, the "individual-to-region" strategy focuses on landslide events, emphasizing slope responses to the impacts of earthquakes. This fundamental difference not only determines the variations in the technical routes adopted by the two strategies for earthquake-induced landslide hazard assessment, but also shapes their unique technical characteristics: The former (region-to-individual) follows a "coarse-to-fine" logic, gradually narrowing down and identifying the hazard-causing bodies of earthquake-induced landslides; the latter (individual-to-region) adopts a "point-to-area" approach, progressively integrating individual slope analyses to form a comprehensive understanding of earthquake-induced landslide hazard across the entire region.

The conflict between the reliability of the assessment results and the convenience of the assessment work is a thorny issue faced by regional earthquake landslide hazard assessment. According to the requirements of assessment work, the balance control between the reliability and convenience of the assessment work is an important factor to be considered in the selection of the strategies and methods for regional earthquake landslide assessment. Obviously, following the assessment strategy from region to individual, the assessment work is from coarse to fine, and the workload of seismic stability analysis of slopes is reduced as much as possible, therefore, this strategy is a relatively fast and efficient assessment strategy. The workload of different assessment methods in the assessment strategy from individual to region mainly depends on the methods for seismic stability analysis of individual slopes. Obviously, the workload of the individual assessment methods based on causality is less than that of the individual assessment methods based on mechanical analysis. For the individual assessment methods based on mechanical analysis, the quasi-static method has the least workload, followed by the Newmark method, and the dynamic time-history method has the heaviest analysis work. This should be the main reason why the dynamic time-history method has not been applied in regional earthquake landslide hazard assessment so far.

3 Problems in Current Research

Up to now, a lot of practice works has been carried out in the assessment of earthquake landslide hazard, however, there are still some problems in the assessment methods that deserve further discussion.

3.1 Problems of the Individual Earthquake Landslide Hazard Assessment

The two types of individual earthquake landslide hazard assessment methods, the qualitative analysis method based on causality and the mechanical analysis method based on physical mechanics mechanism, both have their own characteristics and problems worth noting.

(1) Problems of the qualitative analysis methods

Based on a deep understanding of the physical mechanisms of earthquake landslides, the qualitative analysis method of earthquake landslide hazard is established according to causal relationships between slope seismic stability and relative earthquake landslide factors, including susceptibility conditions and inducing factors. This method focuses on the causal relationships between the susceptibility conditions of earthquake-induced landslides, hazard-inducing factors, and the consequences of seismic slope instability. Based on these causal relationships and large amounts of actual earthquake-induced landslide data, earthquake-induced landslide hazard criteria using earthquake-induced landslide factors is established as a basis for assessing earthquake-induced landslide hazard in a specific future period. The causal qualitative method avoids the labor-intensive process of mechanical stability analysis for slopes, enabling convenient and efficient assessment of earthquake-induced landslide hazard. However, the earthquake-induced landslide criteria obtained via statistical analysis using this method, as well as the underlying earthquake-induced landslide factors (i.e., susceptibility conditions and inducing factors), exhibit strong regional characteristics. Therefore, when extending and applying the earthquake-induced landslide hazard criteria established in one region to other areas, special attention must be paid to the analogy of slope attributes, geological environment, seismic activity, physical geography, and climatic conditions. If necessary, appropriate modifications should be made to the earthquake-induced landslide criteria based on the specific conditions of the target region for application.

(2) Problems of the mechanical analysis methods

The three main methods for mechanical analysis of earthquake-induced landslide hazard—grounded in physical-mechanical mechanisms—are the quasi-static method, Newmark method, and dynamic time-history method. These methods involve different degrees of simplification of the dynamic process of slope seismic response, which in turn gives each method distinct characteristics and inherent limitations.

The quasi-static method simplifies seismic dynamic forces into static forces, which greatly reduces the complexity of slope seismic stability analysis, and it is the simplest method for slope seismic stability analysis. Therefore, it has been widely used in engineering design. However, the biggest problem with the quasi-static method is that it ignores the characteristics of slope dynamic responses to seismic actions and the effects of fatigue and cumulative damages caused by seismic dynamic loads on the rock and soil mass of the slope. As a result, it is possible to overestimate the seismic resistance of the slope, thereby affecting the effectiveness of the seismic design of the slope.

The Newmark method determines the seismic resistance limit of a slope (the critical seismic acceleration a_c of the slope) by the quasi-static method first, and then integrates the seismic acceleration time history acted on the slope, whose amplitude is greater than or equal to the critical seismic acceleration ($a(t) \geq a_c$), twice over time, so as to get the so-called Newmark cumulative displacement $D(t)$ of the slope; furthermore, sets $D(t) \geq D_s$ as the criterion of the instability of the slope caused by seismic action, in which D_s is the set critical value of cumulative displacement for landslide initiation. The use of the quasi-static method in determination of the seismic resistance of slopes avoids dynamic time history analysis, greatly simplifying the analysis work, and thus winning more application opportunities for the Newmark method. However, there are two significant problems with the Newmark method: First, the quasi-static method is still used to determine the seismic resistance of slopes, so the assessment of the seismic instability of slopes by the Newmark method has the same problem as that of the quasi-static method; Second, in the actual earthquake landslide assessment analysis, especially in the assessment of earthquake landslide hazard in future. The calculated Newmark cumulative displacement $D(t)$ is not the displacement of the slope body because the seismic acceleration time history $a(t)$ used in the integrating calculation is not the seismic acceleration time history of the slope body (i.e., the response of the slope body to the seismic cation of the slope sit), but the seismic acceleration time history (seismic ground motion) of the slope site in future provided by the seismic hazard analysis. Therefore, it is not physically reasonable to establish the slope instability criterion with Newmark cumulative displacement.

The dynamic time history method considers the dynamic characteristics of the rock and soil mass of a slope and pays attention to the dynamic responses of the slope to the whole process of seismic action (dynamic time history), and it can provide a more detailed dynamic basis for the seismic design of the slope. Although the dynamic time history method can reveal the dynamic characteristics and seismic dynamic response characteristics of slopes in more depth and detail, this method is much more complex and its workload is much heavier, without the support of strong enough calculation hardware means, the dynamic time history method is difficult to implement. This is the biggest problem of the dynamic time history method and also the main reason for the lag of the development and application of this research method.

3.2 Problems of the Regional Earthquake Landslide Hazard Assessment

According to the existing regional earthquake landslide hazard assessment work, the following three issues deserve attention.

(1) Matching between regional assessment techniques and social demands

Regional earthquake landslide hazard assessment has definite social demand fields, that is, the deployment of rescue work for strong earthquake geological disasters in a certain area, and the defense planning and engineering construction strategic layout for future earthquake disasters. The matching between regional earthquake landslide assessment and social demands involves the adaptation of regional earthquake landslide hazard assessment techniques with different strategies and methods to social needs. From the perspective of social demands, there has not been a detailed description and systematic sorting of relevant needs (such as the deployment of rescue and relief work in the event of a large earthquake, the disaster reduction planning or engineering layout of a certain region in future, etc.); From the perspective of assessment technology, most experts and scholars focus on the earthquake landslide hazard assessment technology and method itself, but often do not pay enough attention to the adaptability of social needs. This current situation may lead to blind development of earthquake landslide hazard assessment and waste of resources. It is essential for social management departments to take the lead and collaborate with experts and scholars to establish an adaptation system that matches the demand fields of earthquake-induced landslide hazard assessment with corresponding assessment methods.

(2) Application of dynamic time history method in regional assessment

Another challenge in regional earthquake-induced landslide hazard assessment is the lack of application of the dynamic time-history method in slope seismic stability analysis. The primary reason for this gap lies in the relative complexity of the dynamic time-history method itself and the substantial workload associated with regional-scale assessments. However, given the superior assessment performance demonstrated by the dynamic time-history method, its exclusion from regional assessments renders such evaluations unable to meet the specific requirements for slope dynamic parameters.

Thus, exploring a set of regional earthquake-induced landslide hazard assessment methods that not only leverage the advantages of the dynamic time-history method but also appropriately control the technical workload of the assessment is a crucial task for optimizing the technical method system of regional earthquake-induced landslide hazard assessment.

(3) Regional assessment considering potential seismic source orientation

An area within an earthquake zone may be affected by earthquakes from different orientations in a certain period of time in the future. Different orientations of the potential seismic sources will result different incidence direction of seismic waves, and the seismic action mode on a slope will also change accordingly. Slopes will have different dynamic responses and resistance to different seismic actions, and the corresponding slope seismic stability will also change. Therefore, the earthquake landslide hazard analysis results that ignore the orientation of potential seismic sources are difficult to accurately reflect the seismic instability and damage of slopes that may occur in a certain period in the future. At present, a probability analysis method for seismic slope instability that considers the influence of potential seismic source orientation has been developed for individual seismic landslide hazard analysis [12,17]. However, the influence of potential seismic source orientation has not been considered in regional earthquake landslide hazard assessment. Therefore, it is imperative to explore regional earthquake landslide hazard assessment methods considering the influence of potential seismic source orientations.

4 Future Research Directions

Clarifying the natural occurrence process of earthquake-induced landslides and examining the current status as well as existing problems of earthquake-induced landslide hazard assessment constitute the fundamental basis for determining the direction of further research on earthquake-induced landslide hazard assessment.

"Seismic energy release—Propagation in medium—Site effect" is the natural process of all earthquake disasters as expressed in Fig. 2. For earthquake landslide events in a certain period of time in future, "Seismic energy release" corresponds to the activities of potential seismic sources in a certain period of time in future; "Propagation in medium " means that the seismic energy radiated by the seismic source spreads and diffuses in the regional crust and shallow ground geological bodies (medium field) in the form of seismic waves, forming an earthquake influence field; "site effect" represents the earthquake landslide caused by the seismic actions of a site in the earthquake influence field. Corresponding to individual an earthquake landslide hazard assessment, the occurrence of earthquake landslide on a single slope depends on the comparison between the seismic resistance of the slope and the strength of the site seismic actions. Extended to regional earthquake landslide hazard assessment, the distribution of regional earthquake landslide hazards depends on the superposition and comparison between the distribution of regional slope seismic resistance (slope seismic resistance field) and the earthquake influence field.

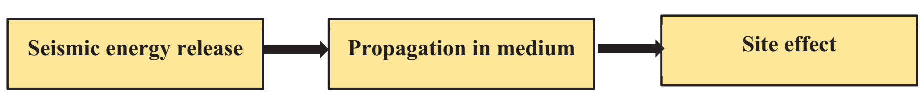

Figure 2: The natural process of earthquake disaster

In the above-mentioned "trilogy" of earthquake landslide hazards ("Seismic energy release—Earthquake influence—Earthquake landslide"), the most eye-catching part is the last one, Earthquake Landslide. The degrees of earthquake landslide hazard depend on the strength comparison between the seismic resistance of slopes and the intensity of site seismic actions. However, the driving force of earthquake landslides originates from the first part of the "trilogy", the seismic energy release of the seismic source, that is, the Earthquake. Without earthquakes, there would be no earthquake landslides. The sources of most catastrophic earthquakes are located in the shallow crust, and the geological tectonic activity of the regional crust and the regional crustal tectonic stress field are the key factors that determine regional seismicity. The middle part of the "trilogy", earthquake influence (field), is the seismic wave field that depends on the regional crust and shallow ground geological bodies (medium field). The seismic dynamics originating from the seismic earthquake source exert seismic actions on slopes through the regional earthquake influence field, causing seismic instability of slopes. The medium fields consisting of regional crustal and shallow surface geological body with different geological structures will produce different regional earthquake influence fields, thus forming different regional earthquake landslide distributions (different realizations of regional earthquake landslide hazards).

In the light of the above understanding of the natural process of earthquake landslides, it is of important scientific significance and engineering application value to carry out methodological research on regional earthquake landslide hazard assessment considering the potential seismic source orientations. The research should follow the main line consisting of the regional slope seismic resistance field, the regional earthquake influence field, and the superposition analysis of the above-mentioned two fields. In consideration of the current status that the influence of potential seismic source orientations has not been considered and the dynamic time history method has not been adopted in regional earthquake landslide hazard assessment, the following research topics should be significant for the improvement of the regional earthquake landslide hazard assessment method system:

(1) Exploring technical solutions for regional earthquake landslide hazard assessment that can take advantage of the dynamic time history method and appropriately control the technical workload.

(2) Establishing conversion relationships between the seismic resistance of slopes (critical seismic accelerations of slopes) and the susceptible conditions for earthquake landslides (slope attribute, geological environment, and geographical and climatic conditions) considering the potential seismic source orientations.

(3) Researching on a regional earthquake landslide hazard assessment method considering potential seismic source orientations.

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References

1. Zou L, Wang C, Zhang H, Wang D, Tang Y, Dai H, et al. Landslide-prone area retrieval and earthquake-inducing hazard probability assessment based on InSAR analysis. Landslides. 2023;20(9):1989–2002. doi:10.1007/s10346-023-02079-7.

2. Šket MB, Zupančič P, Živčić M, Atanackov J, Jamšek RP, Čarman M, et al. The 2021 seismic hazard model for Slovenia (SHMS21): overview and results. Bull Earthq Eng. 2022;20(10):4865–94. doi:10.1007/s10518-022-01399-8.
3. Ma S, Shao X, Xu C, Chen X, Yuan R. Topographic location and connectivity to channel of earthquake- and rainfall-induced landslides in Loess Plateau area. Sci Rep. 2025;15(1):628. doi:10.1038/s41598-024-84885-0.
4. Zhang A, Wang X, Pedrycz W, Yang Q, Wang X, Guo H. Near real-time spatial prediction of earthquake-triggered landslides based on global inventories from 2008 to 2022. Soil Dyn Earthq Eng. 2024;185:108890. doi:10.1016/j.soildyn.2024.108890.
5. Serey A, Sepúlveda SA, Murphy W, De Pascale GP, Petley DN. A revised comprehensive inventory of landslides induced by the 2007 Aysén earthquake, Patagonia. Bull Eng Geol Environ. 2025;84(3):142. doi:10.1007/s10064-024-04057-2.
6. Huang Y, Xu C, He X, Cheng J, Huang Y, Wu L, et al. Distribution characteristics and cumulative effects of landslides triggered by multiple moderate-magnitude earthquakes: a case study of the comprehensive seismic impact area in Yibin, Sichuan, China. Landslides. 2024;21(12):2927–43. doi:10.1007/s10346-024-02351-4.
7. Jin JL, Cui YL, Xu C, Zheng J, Miao HB. Application of logistic regression model for hazard assessment of landslides caused by the 2012 Yiliang Ms 5.7 earthquake in Yunnan Province, China. J Mt Sci. 2023;20(3):657–69. doi:10.1007/s11629-022-7698-6.
8. Chen J, Li L, Xu C, Huang Y, Luo Z, Xu X, et al. Freely accessible inventory and spatial distribution of large-scale landslides in Xianyang City, Shaanxi Province, China. Earthq Res Adv. 2023;3(3):100217. doi:10.1016/j.eqrea.2023.100217.
9. Zei C, Tarabusi G, Ciuccarelli C, Burrato P, Sgattoni G, Taccone RC, et al. CFTIlandslides, Italian database of historical earthquake-induced landslides. Sci Data. 2024;11:834. doi:10.1038/s41597-024-03692-4.
10. Pyakurel A, Dahal BK, Gautam D. Does machine learning adequately predict earthquake induced landslides? Soil Dyn Earthq Eng. 2023;171:107994. doi:10.1016/j.soildyn.2023.107994.
11. Yi Z, Kang J. Finite element-based spatial distribution model for slope stability during earthquakes. Earthq Struct. 2025;28(2):149–59. doi:10.12989/eas.2025.28.2.149.
12. Han S, Sun J, Xiong F. Analysis for site seismic hazard probability considering the orientation distribution of potential seismic sources. Nat Hazards. 2025;121(3):2433–64. doi:10.1007/s11069-024-06900-x.
13. Sun J, Han S, Xiong F, Li G. Probability analysis of slope seismic instability. Xinjiang Geol. 2020;38(2):262–8. (In Chinese). doi:10.3969/j.issn.1000-8845.2020.02.021.
14. Ryanto TA, Yuliastuti ANF. The earthquake hypocenter relocation using double difference method in West Borneo NPP potential site. In: AIP Conference Proceedings. Tangerang Selatan, Indonesia: AIP Publishing; 2022. doi:10.1063/5.0095228.
15. Zhao T, Sun J, Zhang B, Li C. Analysis of slope stability with dynamic overloading from earthquake. J Earth Sci. 2012;23(3):285–96. doi:10.1007/s12583-012-0257-2.
16. Gupta K, Satyam N, Gupta V. Probabilistic assessment of seismically triggered landslide hazard for Uttarakhand (India) in the Western Himalayas. Nat Hazards. 2023;118(1):669–89. doi:10.1007/s11069-023-06023-9.
17. Fu GC, Pan H, Cheng J, Zheng L. Probabilistic hazard analysis of potential seismic landslides: a case study of Longxian County, Shaanxi Province. Acta Seismol Sin. 2023;45(2):341–55. (In Chinese).
18. Xiong F, Sun J, Qi S, Shao A, Han S. Critical peak acceleration characteristics of a slope against actions of P and S waves with different incident directions. Acta Geophys. 2025;73(4):3159–75. doi:10.1007/s11600-025-01555-z.
19. Wang T, Liu JM, Shi JS, Gao MT, Wu SR. Probabilistic seismic landslide hazard assessment: a case study in Tianshui, Northwest China. J Mt Sci. 2020;17(1):173–90. doi:10.1007/s11629-019-5618-1.
20. Keefer DK. Landslides caused by earthquakes. Geol Soc America Bull. 1984;95(4):406. doi:10.1130/0016-7606(1984)95.

21. Tsompanakis Y, Lagaros ND, Psarropoulos PN, Georgopoulos EC. Probabilistic seismic slope stability assessment of geostructures. Struct Infrastruct Eng. 2010;6(1–2):179–91. doi:10.1080/15732470802664001.
22. Ding YH, Wang YQ, Sun JZ, Tang Y. Research on the method for prediction of earthquake-induced landslides and its application to engineering projects. J Eng Geol. 2000;08(04):475–80. (In Chinese).
23. GAO YP, Wang YQ, Xin HB. Application of neural network in predicting seismic stability of slope. J Liaoning Tech Univ. 2001;20(4):431–3. (In Chinese).
24. Sun JZ, Chen X, Wang YQ. The estimation and prediction of the slide and collapse of soil and rock slope triggered by earthquakes with three steps. J Seismol Res. 2004;27(03):256–64. (In Chinese). doi:10.3969/j.issn.1000-0666.2004.03.010.
25. Al-Homoud AS, Tahtamoni WW. SARETL: an expert system for probabilistic displacement-based dynamic 3-D slope stability analysis and remediation of earthquake triggered landslides. Environ Geol. 2000;39(8):849–74. doi:10.1007/s002549900097.
26. Alalade S, Seng C, Chheun D, Choi Y, Kim HJ, Kim SW, et al. Landslide susceptibility mapping using frequency ratio, logistic regression and K-means clustering algorithms: a case study in Inje, South Korea. Environ Earth Sci. 2025;84(13):369. doi:10.1007/s12665-025-12376-0.
27. Waris KA, Fayaz SJ, Reddy AH, Basha BM. Pseudo-static slope stability analysis using explainable machine learning techniques. Nat Hazards. 2025;121(1):485–517. doi:10.1007/s11069-024-06839-z.
28. Huang X, Song D, Chen Z, Xu D, Wang L. Dynamic process analysis of large-scale landslides triggered by the Wenchuan earthquake via the discrete element method. Nat Hazards. 2025;121(6):7683–706. doi:10.1007/s11069-025-07114-5.
29. Chen G, Jin J, Meng X, Qi T, Shi W, Chong Y, et al. Influence of tectonic effects on the formation and characteristics of landslide dams on the NE Tibetan Plateau: a case study in the Bailong River Basin, China. Landslides. 2024;21(9):2135–53. doi:10.1007/s10346-024-02273-1.
30. Gupta N, Das J, Kanungo DP. Earthquake-induced landslide hazard assessment using ground motion parameters: a case study for Bhagirathi Valley, Uttarakhand, India. J Earth Syst Sci. 2024;134(1):5. doi:10.1007/s12040-024-02450-9.
31. Sun D, Xu J, Wen H, Wang D. Assessment of landslide susceptibility mapping based on Bayesian hyperparameter optimization: a comparison between logistic regression and random forest. Eng Geol. 2021;281:105972. doi:10.1016/j.enggeo.2020.105972.
32. Huang Y, Wang W, Zhao L, Xiong M. Fluctuation characteristics of probability density function and first-passage dynamic reliability of slope systems under seismic excitations. Eng Geol. 2022;309:106853. doi:10.1016/j.enggeo.2022.106853.
33. Lashgari A, Rahimi L, Ahmadisharaf E, Barari A. Probabilistic pre-conditioned compound landslide hazard assessment framework: integrating seismic and precipitation data and applications. Landslides. 2025;22(2):413–34. doi:10.1007/s10346-024-02371-0.
34. Gong W, Zekkos D, Clark M. A pseudo-3D methodology for regional-scale back-analysis of earthquake-induced landslides. Eng Geol. 2023;325:107277. doi:10.1016/j.enggeo.2023.107277.
35. Xiong F, Huang R, Sun J, Dong S, Hao M, Li G. Dynamic response of loess slope with uniform and isotropic layers to shear waves with different incident directions. In: Global view of engineering geology and the environment. Boca Raton, FL, USA: CRC Press; 2013. p. 845–9. doi:10.1201/b15794-135.
36. Nadi B, Tavasoli O, Kontoni DN, Tadayon A. Investigation of rock slope stability under pore-water pressure and structural anisotropy by the discrete element method. Geomech Geoengin. 2021;16(6):452–64. doi:10.1080/17486025.2019.1680879.
37. Karl T. Mechanism of landslides. In: Application of geology to engineering practice. New York, NY, USA: Geological Society of America; 2015. p. 83–123. doi:10.1130/berkey.1950.83.
38. Department of Construction of Heavy Industry Enterprises of the Soviet Union. Building code for earthquake zone (IICII-101-51). Beijing, China: Textile Industry Press; 1954. (In Chinese).

39. Tamrakar A, Chen S. Comparison of the seismic design code for buildings of Nepal with the Chinese, European and American seismic design codes. In: The Thirtieth KKHTCNN Symposium on Civil Engineering; 2017 Nov 2–4; Singapore.
40. Toska K, Hofer L, Faleschini F, Zanini MA, Pellegrino C. Seismic behavior of damaged RC columns repaired with FRCM composites. Eng Struct. 2022;262:114339. doi:10.1016/j.engstruct.2022.114339.
41. Chen X, Wu S, Li J, Guan Z, Xiang N. Seismic performance assessment and design procedure of base-isolated bridges with lead-rubber-bearing and negative stiffness springs (LRB-NS). Eng Struct. 2024;306:117871. doi:10.1016/j.engstruct.2024.117871.
42. Sun HY, Wang X, Yu Y, Shu JW, Wang TL, Luo R, et al. A new anchor-siphon drainage combined method used for slope stabilization. J Mt Sci. 2023;20(11):3295–311. doi:10.1007/s11629-023-7969-x.
43. Iliopoulos A. Design of steel-concrete composite bridges to Eurocodes. Boca Raton, FL, USA: CRC Press; 2013.
44. Newmark NM. Effects of earthquakes on dams and embankments. Géotechnique. 1965;15(2):139–60. doi:10.1680/geot.1965.15.2.139.
45. Jibson RW. Predicting earthquake-induced landslide displacements using Newmark's sliding block analysis. Transp Res Board Transp Res Rec. 1993;1411:9–17.
46. Jibson RW. Regression models for estimating coseismic landslide displacement. Eng Geol. 2007;91(2–4):209–18. doi:10.1016/j.enggeo.2007.01.013.
47. Jibson RW, Harp EL, Michael JA. A method for producing digital probabilistic seismic landslide hazard maps. Eng Geol. 2000;58(3–4):271–89. doi:10.1016/S0013-7952(00)00039-9.
48. Mitseas IP, Ni P, Fragkoulis VC, Beer M. Survival probability surfaces of hysteretic fractional order structures exposed to non-stationary code-compliant stochastic seismic excitation. Eng Struct. 2024;318:118755. doi:10.1016/j.engstruct.2024.118755.
49. Seed HB, Lee KL, Idriss IM, Makdisi FI. The slides in the San Fernando dams during the earthquake of February 9, 1971. J Geotech Engrg Div. 1975;101(7):651–88. doi:10.1061/ajgeb6.0000178.
50. Seed HB, Idriss IM, Lee KL, Makdisi FI. Closure to "dynamic analysis of the slide in the lower San Fernando dam during the earthquake of February 9, 1971. J Geotech Engrg Div. 1977;103(1):64–7. doi:10.1061/ajgeb6.0000371.
51. Alonso EE, Gens A. Aznalcóllar dam failure. Part 3: dynamics of the motion. Géotechnique. 2006;56 (3):203–10. doi:10.1680/geot.2006.56.3.203.
52. Fan B, Cheng Z, Wang T, Wang S. Dynamic response characteristics and liquefaction analysis of a phosphogypsum tailings dam. Int J Geomech. 2025;25:05024012. doi:10.1061/ijgnai.gmeng-9229.
53. Pang R, Xu B, Zhou Y, Song L. Seismic time-history response and system reliability analysis of slopes considering uncertainty of multi-parameters and earthquake excitations. Comput Geotech. 2021;136:104245. doi:10.1016/j.compgeo.2021.104245.
54. Chen G, Xia M, Thuy DT, Zhang Y. A possible mechanism of earthquake-induced landslides focusing on pulse-like ground motions. Landslides. 2021;18(5):1641–57. doi:10.1007/s10346-020-01597-y.
55. Chen M, Tang C, Xiong J, Shi QY, Li N, Gong LF, et al. The long-term evolution of landslide activity near the epicentral area of the 2008 Wenchuan earthquake in China. Geomorphology. 2020;367:107317. doi:10.1016/j.geomorph.2020.107317.
56. Fu H, Zhao Y, Zhou M, Li Q. Seismic stability analysis of bidirectional jointed rock slope. Bull Eng Geol Environ. 2025;84(4):168. doi:10.1007/s10064-025-04188-0.
57. He J, Wang Y, Zhao J, Zhang Y, Wu J, Wei J, et al. Seismic response of an irregular slope containing surficial weak layer and internal fractures in Dadu River, southwest China. Landslides. 2024;21(3):621–40. doi:10.1007/s10346-023-02171-y.

58. Chung CC, Li ZY. Rapid landslide risk zoning toward multi-slope units of the Neikuihui tribe for preliminary disaster management. Nat Hazards Earth Syst Sci. 2022;22(6):1777–94. doi:10.5194/nhess-22-1777-2022.
59. Yalcin Kavus B, Taskin A. Assessment of landslides induced by earthquake risk of Istanbul: a comprehensive study utilizing an integrated DFS-AHP and DFS-EDAS approach. Soil Dyn Earthq Eng. 2025;191:109285. doi:10.1016/j.soildyn.2025.109285.
60. Xu D, Song D, Wang L, Huang X, Chen Z. Numerical investigation on seismic response characteristics and deformation mechanism of high-steep rock slopes containing weak structural planes using time-frequency joint analysis. Bull Eng Geol Environ. 2025;84(2):98. doi:10.1007/s10064-025-04143-z.
61. Zheng X, Sun J, Yao L, Liu L, Shao A. A three-dimensional oblique incidence method based on stress time-history functions of seismic body waves. Environ Earth Sci. 2018;77(14):528. doi:10.1007/s12665-018-7691-0.
62. Fan G, Zhang LM, Li XY, Fan RL, Zhang JJ. Dynamic response of rock slopes to oblique incident SV waves. Eng Geol. 2018;247:94–103. doi:10.1016/j.enggeo.2018.10.022.
63. Wang R, Ding M, Wang Y, Xu W, Yan L. Field characterization of landslide-induced surge waves based on computational fluid dynamics. Front Phys. 2022;9:813827. doi:10.3389/fphy.2021.813827.
64. Saint Fleur N, Dessable JE, Saint-Preux G, Calais É, Feuillet N, Boisson D, et al. Tectonic, topographic, geologic, and hydroclimatic influence on crack formation during the 2021 Haiti earthquake. Geochem Geophys Geosyst. 2024;25(7):e2023GC011255. doi:10.1029/2023gc011255.
65. Miles SB, Ho CL. Rigorous landslide hazard zonation using Newmark's method and stochastic ground motion simulation. Soil Dyn Earthq Eng. 1999;18(4):305–23. doi:10.1016/S0267-7261(98)00048-7.
66. Miles SB, Keefer DK. Evaluation of CAMEL—comprehensive areal model of earthquake-induced landslides. Eng Geol. 2009;104(1–2):1–15. doi:10.1016/j.enggeo.2008.08.004.
67. Nandi A, Shakoor A. Application of logistic regression model for slope instability prediction in Cuyahoga River Watershed, Ohio, USA. Georisk Assess Manag Risk Eng Syst Geohazards. 2008;2(1):16–27. doi:10.1080/17499510701842221.
68. Yilmaz I. Landslide susceptibility mapping using frequency ratio, logistic regression, artificial neural networks and their comparison: a case study from Kat landslides (Tokat-Turkey). Comput Geosci. 2009;35(6):1125–38. doi:10.1016/j.cageo.2008.08.007.
69. Djukem DLW, Fan X, Havenith HB. Effective prediction of earthquake-induced slope displacements, considering region-specific seismotectonic and climatic conditions. Nat Hazards. 2025;121(9):10517–52. doi:10.1007/s11069-025-07200-8.
70. Li XJ, Gao MT, Xu WJ. Probabilistic seismic landslide hazard analysis method based on Newmark model: a case study of Tianshui area in Gansu province. Acta Seismol Sin. 2019;41(6):759–807. (In Chinese).
71. Zhao HJ, Ma FS, Li ZQ, Guo J, Zhang JX. Parameter optimization and application of probabilistic earthquake landslide hazard model based on Newmark model: a case study of Ludian earthquake region. Earth Sci. 2022;47(12):401–4416. (In Chinese).