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Disaster Prevention and Resilience

Review

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From slope seismic resilience to regional road network resilience: an integrated framework for evaluating the seismic resilience of mountainous road networks

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Abstract

A systematic review was conducted, ranging from the seismic resilience of single slope engineering structures as disaster-bearing bodies to their transformation into disaster-inducing bodies owing to seismic dynamic instability. The resilience of slopes is considered with regard to regional transportation networks, which are most severely threatened by earthquake-induced landslide disasters. For the engineering structure of a single slope as a disaster-bearing body, the stage before the slope engineering loses stability can be considered as the first stage of slope seismic resilience evaluation. This review summarizes the latest progress in seismic resilience evaluation and reinforcement design from the perspective of engineering seismic resilience. In response to the lack of definition for the resilience of existing regional road networks to earthquake-induced landslide impacts during the review, the second stage involves the transformation of the seismic dynamic instability of regional slopes into landslide disasters; resilience is defined as the global system reliability of the regional road network in this study. From the perspective of network reliability, an assessment framework for the resilience of the regional transportation network against seismic landslide disasters is systematically proposed in this study. In accordance with high-dimensional nonlinear network dynamics theory, this paper highlights the future research direction of introducing high-dimensional network dynamics theory into the disaster resilience of regional road networks affected by landslide disasters.

Keywords: Slope engineering, seismic landslide disaster, road network, global system resilience, assessment framework

INTRODUCTION

Resilience is the latest concept in various disaster prevention and control fields, applicable to both natural and man-made disasters. Without loss of generality, resilience refers to the ability of a system to resist, absorb, and adapt to impact disturbances without collapsing and quickly restoring to an original or improved functional state[1]. Various studies have reported that there are no significant differences in the definitions of resilience among different disciplines and research fields, and different definitions share the following characteristics: (1) defining resilience from results or processes; and (2) the premise of definition is based on the fact that the object or system incurs particular damages caused by external interference. However, owing to differences among disciplines and research objects, systematic analysis has revealed that there are dozens of resilience definitions at present[2], and resilience is a fundamental concept in many disciplines. Moreover, resilience is also a fundamental attribute of complex dynamic systems[3]. Therefore, it is necessary to systematically and comprehensively sort out the different connotations and definitions of resilience in different disciplines.

In the field of engineering science, particularly in the field of infrastructure disaster prevention (earthquakes, typhoons, rainstorms, floods, and so on), various studies have investigated the concept of resilience-based disaster prevention and conducted relevant research. Regarding slope engineering, although slope engineering and superstructures belong to the same engineering category, the understanding of the resilience of slope engineering, particularly the resilience of slope engineering with seismic dynamic excitation as a complex dynamic system, is completely different from that of superstructures. Presently, the design of slope engineering based on resilience, particularly the seismic resilience of slopes, is gradually becoming a research hotspot and receiving widespread attention. In addition, more importantly, research on the seismic resilience of slopes has evolved from research on regional earthquake and landslide disasters to research on the resilience of regional road networks. Of course, the resilience of the regional road network to disasters is still in its infancy. How do we define and measure the resilience of regional road networks? How do we establish a resilience assessment framework for regional road networks under earthquake-triggered landslide impacts? At present, these are the first issues to be addressed in the resilience assessment and design of regional road networks against disasters such as earthquake-triggered landslides, especially considering the physical mechanisms of external environmental excitation and the interaction between seismic landslide disasters and road networks. Therefore, this study attempted to systematically review the latest research progress on the seismic resilience of individual slope engineering and the resilience of regional infrastructure to earthquake landslide disasters from the perspectives of high-dimensional network systems and complex dynamic systems, combined with the physical mechanism of the transformation of slope engineering from a disaster-bearing body to a disaster-inducing body. On this basis, combined with relevant theories from other basic disciplines such as nonlinear complex dynamical systems, graph theory, and stochastic dynamics theory, the potential directions of future research are pointed out.

SEISMIC RESILIENCE OF SLOPE ENGINEERING

The essential role of slope engineering is to act as an engineering structure and disaster-bearing body and withstand the impact of seismic dynamic disasters before it loses stability under seismic dynamic action. At this point, the seismic resilience of slope engineering should be completely similar to that of the upper building structure, which also has seismic robustness under earthquake impact and rapid recovery after earthquake disasters. Slope engineering is a general concept and generally includes temporary and permanent geological engineering similar to slopes, particularly earth dams, excavated building foundations, and open cuts for expressway embankment and slope engineering[4]. Therefore, considering the characteristics of seismic design and evaluation of slope engineering, combined with the definition of resilience for engineering structures[5], the seismic resilience of slope engineering can be characterized by two indicators: robustness and recoverability. Figures 1 and 2 help gain a specific understanding of the seismic resilience of a slope. Obviously, the concept and definition of resilience encompasses the seismic resilience evaluation or design (re-evaluation) of slope engineering, which is a quantitative characterization procedure for determining the robustness (vulnerability) and recoverability (recovery process) of a slope subjected to seismic dynamic excitation. In addition, there is inevitably randomness or uncertainty in the evolution process of seismic resilience in slope engineering or regional road networks. These uncertainties in the seismic resilience assessment of slope engineering or regional road networks need to be quantitatively characterized based on stochastic dynamics, and the probability density functions (PDFs) in Figures 1 and 2 are the most intrinsic expressions of stochastic systems[6]. In addition, although Figures 1 and 2 are conceptual diagrams in this study, the seismic resilience curve for specific slope engineering can still be determined by selecting appropriate overall performance indicators (such as factors of safety or reliability) and using numerical simulation methods based on physical mechanisms. It should also be noted that the seismic resilience of slope engineering is not entirely the same in connotation as the resilience of superstructures such as buildings or bridges, especially in terms of recoverability after earthquake disasters. For slopes, if they become unstable during an earthquake or landslide, the soil flowing down will only be cleared if it affects road traffic, and there is no need to restore the original slope. Therefore, the recoverability referred to here is determined through numerical simulation analysis and is not a true recovery process. If it is found that the slope will lose stability under potential seismic dynamic excitation in the future, reinforcement measures should be taken to make it resistant to seismic dynamic impacts. Of course, the recovery time here can be determined by the construction time required for different reinforcement measures, and the performance indicators of the recovery process can also be the aforementioned factor of safety or reliability.

As shown in Figure 1, owing to the combined effects of randomness and spatiotemporal variability in the deterioration process of geomaterial parameters, in addition to the randomness of seismic excitation, slope engineering may exhibit different paths of seismic resilience evolution. Here, $Q(t)$ is a specific seismic resilience representation of the functionality of the slope (such as seismic stability or seismic stability reliability); $\boldsymbol{x}_i(i = 1, 2, ..., n)$ is a random vector characterizing the randomness in the slope system; $f_n(x)$ is a PDF characterizing the randomness in a specific path of resilience evolution. Moreover, regarding the specific evolution process of seismic resilience in slope engineering, Figure 2 shows that for slope engineering similar to construction projects, the seismic resilience of the slope evolves over the service time owing to the deterioration and reinforcement effects of the geomaterials comprising the slope and the combined effects of possible seismic excitations during service. Moreover, in Figure 2, the seismic vulnerability of the slope engineering during service is the part where the seismic performance of the slope engineering decreases under seismic dynamic excitation, and the difference value between this state and full function is the seismic robustness of the slope engineering. The seismic vulnerability here refers to the portion of the preset performance of the slope engineering (yellow dashed line in Figure 2) that decreases under possible seismic excitation. Moreover, after an earthquake, due to the reinforcement effect, the seismic performance of slope engineering after reinforcement may be higher than the original preset performance level. However, during the long-term service of slope engineering, the mechanical properties of slope geomaterials and support structures may deteriorate under the complex external environment.

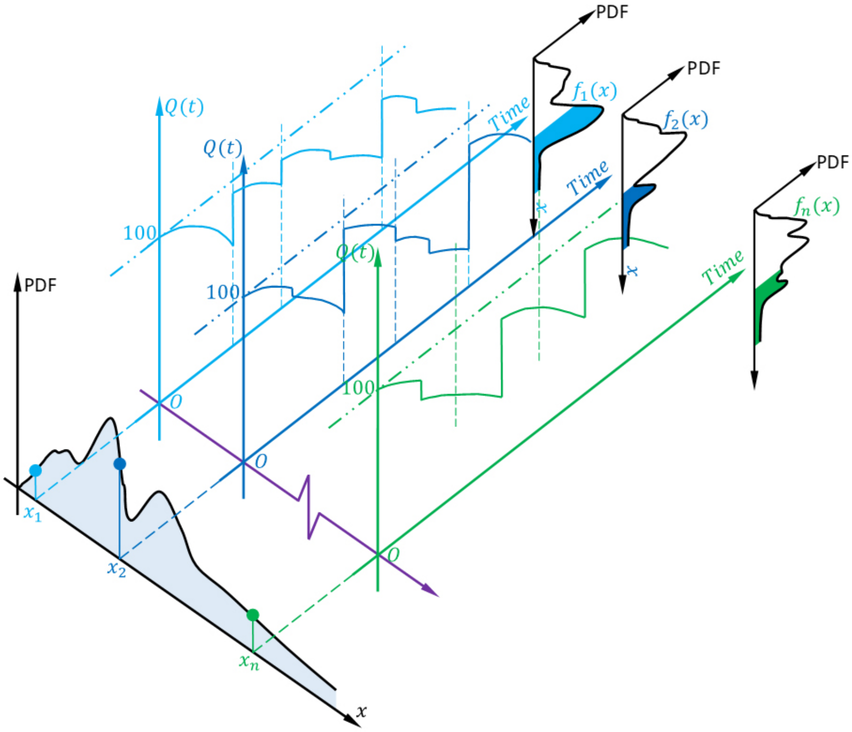

Figure 1. 3-D seismic resilience concept of slope engineering expanding in evolutionary paths.

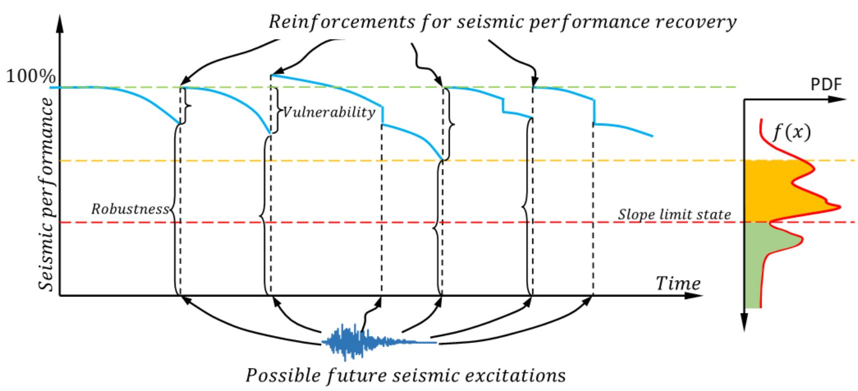

Figure 2. Seismic resilience concept and definition of slope engineering.

Therefore, under potential seismic excitations in the future, the seismic performance of slope engineering will deteriorate, which increases the seismic vulnerability of slope engineering and makes the seismic resilience of slope engineering evolve over time, and it is a function of time[7].

Resilience has been simply defined as the ability to survive during or after a disaster. Some studies have investigated the survival ability of mountain communities after landslides based on disaster surveys using geographic information systems (GIS). Owing to a limited understanding of the concept of resilience, early resilience assessments only focused on robustness similar to one part of the current concept of resilience without considering the post-disaster recoverability of communities impacted by landslides[8]. Additionally, a probabilistic seismic resilience assessment model for general coastal artificial slopes (harbors) has been proposed, with consideration of the uncertainties in seismic motion, structural components, repair process, and service requirements. This model considers the seismic resilience of general coastal slope engineering subjected to scenario-based earthquake excitation and evaluates the seismic resilience of engineering structures based on numerical simulation analysis. The research represents a pioneering effort in the field of generalized slope engineering with particular emphasis on the restoration process, which serves as a highlight of its contributions[9]. In fact, slope engineering has certain differences compared with other engineering structures, particularly building structures. For slope engineering structures, except embankments and earth dams, when instability or landslides are caused by seismic excitation, most slope engineering is excavated from the earthquake-induced landslide soil, and there is almost no need to restore the slope itself. Presently, research on the recovery model of the seismic resilience of slope engineering is almost entirely based on the reinforcement of slope engineering and the restoration of potential seismic damage based on scenario-based seismic excitation. However, this approach fails to address the actual seismic damage to slope engineering, including instability and sliding under earthquake action. Therefore, even at present, although it is widely believed that resilience-based seismic design is the most advanced concept of earthquake resistance, the seismic evaluation of slope engineering mainly focuses on seismic robustness or vulnerability. For example, many studies on the seismic performance or vulnerability (fragility) of slope engineering and its related reinforcement structures are based on statistical data obtained by on-site slope earthquake disaster investigation, analytical methods, and numerical simulation methods based on physical mechanisms[10-16].

Notably, some studies have emphasized that the recoverable part of slope resilience assessment is based on the potential failure modes preset by humans and on analytical methods. The generalization of slope systems that are characterized by the strong nonlinearity of geotechnical materials is difficult. Moreover, the resilience assessment of these slopes does not consider seismic dynamic excitation[17,18]. Some scholars have reported that the use of linear analytical models in developing long-term recovery models may be unreasonable[19]. Research on the seismic resilience of slope engineering is easy to understand but difficult to implement. Moreover, there are few reports on the evaluation of seismic resilience in slope engineering, and studies based on dynamics and simulation, which emphasize the recovery process, are particularly lacking. In this regard, the latest research has only established a preliminary framework for evaluating the seismic resilience of slope engineering but lacks in-depth investigation and specific applications to slope engineering[20].

In summary, there are currently three main types of seismic resilience assessment for slope engineering[21]: (1) empirical model and statistical analysis based on previous seismic disaster investigation data for slope engineering; (2) simulation-based evaluation models, which mainly analyze the seismic robustness (vulnerability) and reinforcement recovery process of slope engineering using numerical simulation methods based on the physical mechanism of slope deformation under seismic dynamic action to evaluate the seismic resilience of the slope; and (3) decision-based evaluation models, which are mainly used to determine the optimal restoration process of slopes based on decision theory and optimization theory. Considerable progress has been made in the study of seismic dynamic safety in slope engineering, particularly regarding robustness assessment, which is a seismic resilience assessment approach for slope engineering. Noteworthy achievements have been accomplished by the nonlinear seismic dynamic vulnerability (fragility) assessment of slope engineering, and diverse vulnerability assessment methods have been established[22-24]. These methods can effectively consider the coupling effects of the randomness (frequency and intensity) of earthquake ground motion, spatial variability of geotechnical materials, and strong nonlinearity under seismic dynamic effects. However, other aspects of seismic resilience assessment in slope engineering, such as the recovery process, are still in a relatively early stage of development and may become future research directions. At present, the evaluation of seismic resilience, robustness or vulnerability, and subsequent reinforcement performance recovery of individual slopes are good characterizations of the seismic resistance of slopes. Due to different reinforcement measures and the complexity of the external environment in which the slope is located, there is inevitably randomness in both external dynamic excitation and the evolution of the geomaterials. Therefore, the time evolution of seismic dynamic reliability of individual slopes is an important indicator of their seismic resilience. Overall, the above-mentioned various so-called resilience assessment models are not proposed for slope engineering but simply a simple extension of the seismic reliability assessment results of building structures. That is to say, even in single slope engineering, the research on seismic resilience is still in its early stages, and only a simple application and promotion of the research results on slope reliability and building structure resilience evaluation have been made. In this way, let alone the research on the resilience assessment of regional road networks affected by earthquake landslide disasters.

GLOBAL RESILIENCE OF THE REGIONAL ROAD NETWORK SUBJECTED TO SEISMIC LANDSLIDE IMPACT

The previous section discussed the seismic resilience of slope engineering as a disaster-bearing body before the occurrence of instability and landslides. The state-of-the-art research on the seismic resilience of slope engineering is systematically reviewed from two aspects: robustness and recoverability. When a slope project loses stability under strong seismic forces and a landslide occurs, the slope ceases to be a disaster-bearing body and is transformed into a disaster-inducing body. The dynamic impact of earthquakes and landslides severely threatens the safety and long-term operation of infrastructure in adjacent areas. At this point, the resilience assessment shifts from quantifying the seismic resilience of slope engineering to characterizing the resilience of regional infrastructure against earthquake and landslide disasters. Generally, regional infrastructure affected by earthquake and landslide disasters may involve regional road networks, railway networks, communities, official water and gas supply networks, and regional power grids[25,26]. Obviously, evaluating the dynamic impact of regional infrastructure against earthquake and landslide disasters is a very large and complex topic. To focus on and simplify the problem, in this section, regional infrastructure mainly refers to high-intensity mountain canyon roads or railway networks. The robustness mentioned above is one aspect of resilience and refers to the ability of a system to withstand faults and disturbances without losing its function. In network science, robustness measures the ability of a system to maintain connectivity when some nodes or edges are damaged. In any case, resilience is an inherent persistent attribute of general dynamic systems. Regardless of whether the resilience of a system is evaluated or measured, the essence of a dynamic system also evolves over time, and it is evident that resilience also has time-varying characteristics.

Generally, regional road networks in mountainous areas consist of roads, bridges, tunnels [Figure 3], or underground engineering. When an earthquake occurs, tunnels and underground engineering are strongly constrained by the surrounding soil. Because tunnels and underground engineering typically vibrate synchronously with the rock and soil, they are generally considered to have good seismic performance. For example, in the Wenchuan earthquake, 98.2% of tunnels were quickly repaired and opened to traffic after the earthquake because they did not incur damage or the damage was minor. Compared with tunnels or underground projects, regional roads and bridges are more vulnerable to dynamic impact damage induced by strong earthquakes. Therefore, the connectivity or global service performance of regional road networks is determined by the seismic performance of mountainous roads and bridges. Historical earthquake damage surveys have shown that the damage and failure of bridges and roads in mountainous areas are mainly caused by direct seismic dynamic excitation, while in non-mountainous areas, the damage and failure of bridges are mainly caused by the impact of landslides resulting from the instability of mountain slopes. For example, after the Wenchuan earthquake, the loss of transport infrastructure in Sichuan Province reached

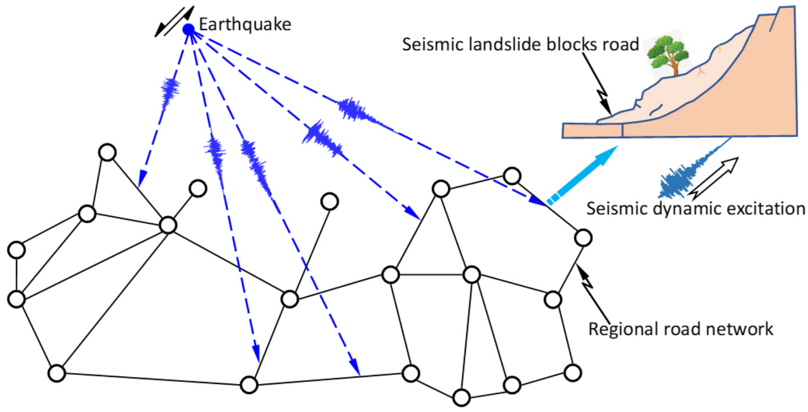

Figure 3. Earthquake-induced landslides affect and block regional road networks.

58.3 billion RMB. However, from the perspective of the causes of damage, the proportion of direct damage caused by earthquakes is very small, with the vast majority being caused by indirect reasons such as landslides. Under strong seismic excitation, road network slopes are prone to seismic hazards, such as landslides, collapses, cracks, or subsidence, which wash away roads and bridges, bury tunnel openings, and so on. As can be seen, the overall service resilience of the regional road network in mountainous areas is mainly affected by the impact of earthquake-induced landslide disasters. Therefore, when slope engineering becomes unstable and develops a landslide during or after an earthquake, the evaluation of the seismic resilience of engineered slopes will shift toward investigating the disaster resilience of network infrastructure, such as highways and railways, which are threatened by earthquake-induced landslides. This study mainly focuses on the road network in mountainous areas. This is because, compared to other urban road networks, mountainous roads are often the only lifeline projects in the region, and there are almost no backup roads that can be bypassed. Moreover, the road network in mountainous areas not only affects post-earthquake disaster rescue but also relates to local reconstruction and economic recovery after the disaster. Meanwhile, compared to general urban road networks, the redundancy of mountainous road networks is much smaller, and recoverability is its most important attribute. It not only needs to be restored after disasters but also needs to be quickly restored. Comparatively speaking, the road network in mountainous areas places greater emphasis on overall disaster resilience.

This section discusses, reviews, and summarizes the state of the art in research related to the resilience of regional road networks against earthquake-induced landslides. Additionally, for bridges and tunnels in mountainous areas, although they may also be directly affected by seismic excitation, the main factor causing bridge damage and tunnel failure by burial is the landslide disaster triggered by earthquakes[27-29]. Therefore, the main cause of the critical failure and cascading collapse of the regional road network system is the spatiotemporal distribution of regional landslide disasters caused by seismic motion. Regarding the resilience of regional road networks to earthquake-triggered landslide disasters, this study focused on the damage caused by landslides, such as the erosion or blockage of regional roads.

Some studies have characterized the distribution of regional ground motion intensity through the peak ground acceleration (PGA). They simply define the vulnerability V of regional roads as the ratio of the peak acceleration that the roads can withstand to the possible acceleration of the site and then determine the economic loss D of the regional road network as a function of PGA and V, that is, $D = f(PGA, V)$. Finally, the authors simply equated the economic loss D with the seismic resilience of the road network[30]. Although the authors considered the propagation of the randomness of PGA, the characterization of the vulnerability and resilience of regional road networks is too simple and does not consider the nonlinear interaction between the seismic excitation and regional road networks or the intensity and frequency spectrum characteristics of seismic excitation. A different study considered the spatial variability of seismic ground motion. Based on the material point method for analyzing the large deformation of landslide soil triggered by earthquakes, the reliability of the road network was analyzed based on the assumed spatial correlation of landslides[31], but a specific method for analyzing the reliability of the regional road system as a network was not provided. Regarding the post-disaster recovery of road networks, a previous study considered the regional transportation system as a network, defined the resilience of the network as a piecewise linear function, and determined the optimal recovery strategy using optimization algorithms[32]. Owing to the combined explosion of the magnitude of the network system computation as the nodes and edges increase, the above-mentioned study only selected the affected areas of the road network for optimization analysis.

Another study defined road network resilience as the integral of the reciprocal of the total travel time of the road network and obtained a very similar evolution process of the resilience curve. On this basis, an extremely simplified analysis framework for a road network under the combined action of earthquakes and tsunamis was proposed, and the importance of single nodes, such as earth dams and bridges, in overall seismic resilience assessment was investigated using the proposed network[33]. In recent years, many similar studies[21,34-36] have been conducted. However, most studies on the robustness of road networks to disasters and post-earthquake recovery are too simplistic, that is, even simpler than the evaluation of seismic resilience in individual slope engineering. In addition to a few studies that considered the earthquake motion as a stochastic process of the strength frequency and also considered the strong nonlinearity of slopes under the dynamic action of earthquake motion[37], most studies only considered the earthquake motion as PGA and did not carry out a nonlinear dynamic time history analysis of the entire process of the seismic deformation of slopes. In fact, the resilience assessment of regional road networks under the impact of earthquake-induced landslide disasters should start with the physical process of nonlinear deformation, instability, and, ultimately, the formation of landslide impact disasters caused by regional slopes under seismic dynamic action. This process involves the following aspects:

(1) Describing the randomness of the spatial distribution of regional seismic motion and obtaining the seismic time history field (displacement or acceleration) of the regional site. As shown in Figure 3, owing to the influence of the earthquake propagation path and site characteristics, the seismic excitation of slopes at different locations in the road network area is not completely identical.

(2) Investigating the dynamic interaction between earthquake-induced landslide disasters and regional road networks from a physical perspective, from the nonlinear finite element analysis of the small deformation of slope earthquakes to the calculation of large deformation of earthquake-induced landslides.

(3) Describing and defining the robustness of regional road networks under earthquake-induced landslide disasters and the recovery process after disasters.

The above-mentioned issues are somewhat involved in the current process of earthquake-induced landslide resistance in regional road networks but have not been thoroughly investigated and may become the direction and focus of future research. The specific implications are analyzed in detail in next section.

ASSESSMENT FRAMEWORK FOR REGIONAL ROAD NETWORK RESILIENCE

This section discusses in detail several aspects that may be involved in the evaluation of the resilience of regional road networks to earthquake-induced landslide disasters. The specific regional road network resilience assessment process is shown in Figure 4. It mainly includes three parts: (1) the seismic field of the site; (2) analysis of the entire process of nonlinear deformation to the large deformation flow of regional slopes under seismic dynamic action, and the interaction between landslide disasters and road networks; and (3) assessment of regional road network resilience and optimization recovery strategy. Among the above three parts, in Figure 4, the first part (A) focuses on the external dynamic environment of the mountainous road network, namely the seismic dynamic impact of the site where it is located. The main research content is characterizing the ground motion excitation of the site and considering the randomness of ground motion in terms of frequency, intensity, *etc*. The second part (B) is to investigate the dynamic stability state of the slope of the site where the mountain road network is located under seismic excitation. If these slopes are stable under strong earthquakes, there will be no co-seismic landslides affecting the road network during the current earthquake. Due to the long-term effects of earthquake disasters, landslides may also occur several years later, which can make this problem more complex. If an earthquake or landslide occurs, it will inevitably affect the road network to varying degrees. At this point, through the physical process of landslide impact on the road network, the randomness of ground motion is transferred from the seismic instability of the slope to the connectivity of the road network, which needs to be measured through network reliability. The third part (C) is mainly to determine the overall connectivity of the road network represented by the network reliability under the impact of earthquake-triggered landslide disasters, that is, the disaster resistance robustness of the road network. Under the optimization strategy, the entire process of gradually transforming and restoring the state phase $i(i = 1, 2, ..., n)$ of the road network from the impact of landslide disasters, that is, the overall resilience of the road network to seismic disasters. Specifically, the seismic resilience assessment flow chart of the regional road network is shown in Figure 5. In this section, the above points are introduced in detail. Unlike the aforementioned single slope engineering, there is currently no unified understanding of the resilience of road networks affected by landslides caused by earthquakes, and there is also a lack of a standardized method for evaluating their seismic resilience. This study suggests that network resilience should be understood from the perspective of network reliability based on graph theory. In addition, the biggest advantage of the seismic resilience assessment framework for this regional road network is that the entire assessment process is based on physical mechanisms. It can not only characterize the strength of the external dynamic disaster environment (earthquake excitation) but also consider the entire process of slope from nonlinear deformation to dynamic instability under earthquake dynamic action. It also examines the impact of landslides on the road network from the perspective of dynamic interaction and measures the resilience of the road network through overall network reliability. It is undeniable that while this framework has its advantages, it also inevitably has some certainty that analysis solely based on physical mechanisms will result in relatively large computational complexity and time consumption, but the evaluation accuracy will be very high. Most importantly, the vital feature of the regional road network disaster resilience assessment framework proposed by this study is that it defines the quantification measure of the disaster resilience of the regional road network.

Understanding the physical process of "landslide - transport network" interactions

When an earthquake triggers a landslide in a slope project, the large deformation of the soil flowing through the landslide will affect the regional road network. To improve the characterization of the physical process of the interaction between large-deformation soil and roads, it is necessary to carry out a numerical analysis of the large deformation flow impact process based on physical mechanisms so as to carry out dynamic analysis for road networks. Presently, there are many advanced numerical algorithms in this field, and these algorithms can be applied to the interaction analysis of regional landslides and road networks. Examples include the reproducing kernel particle method[38], smoothed particle hydrodynamics[39,40], discontinuous deformation analysis[41], and material point method[42]. Explaining how these methods can be combined with the spatial variability of seismic excitation[43,44] may be a future research direction. There are a large number of slopes in the area where the road network is located. It involves both the evaluation of the dynamic

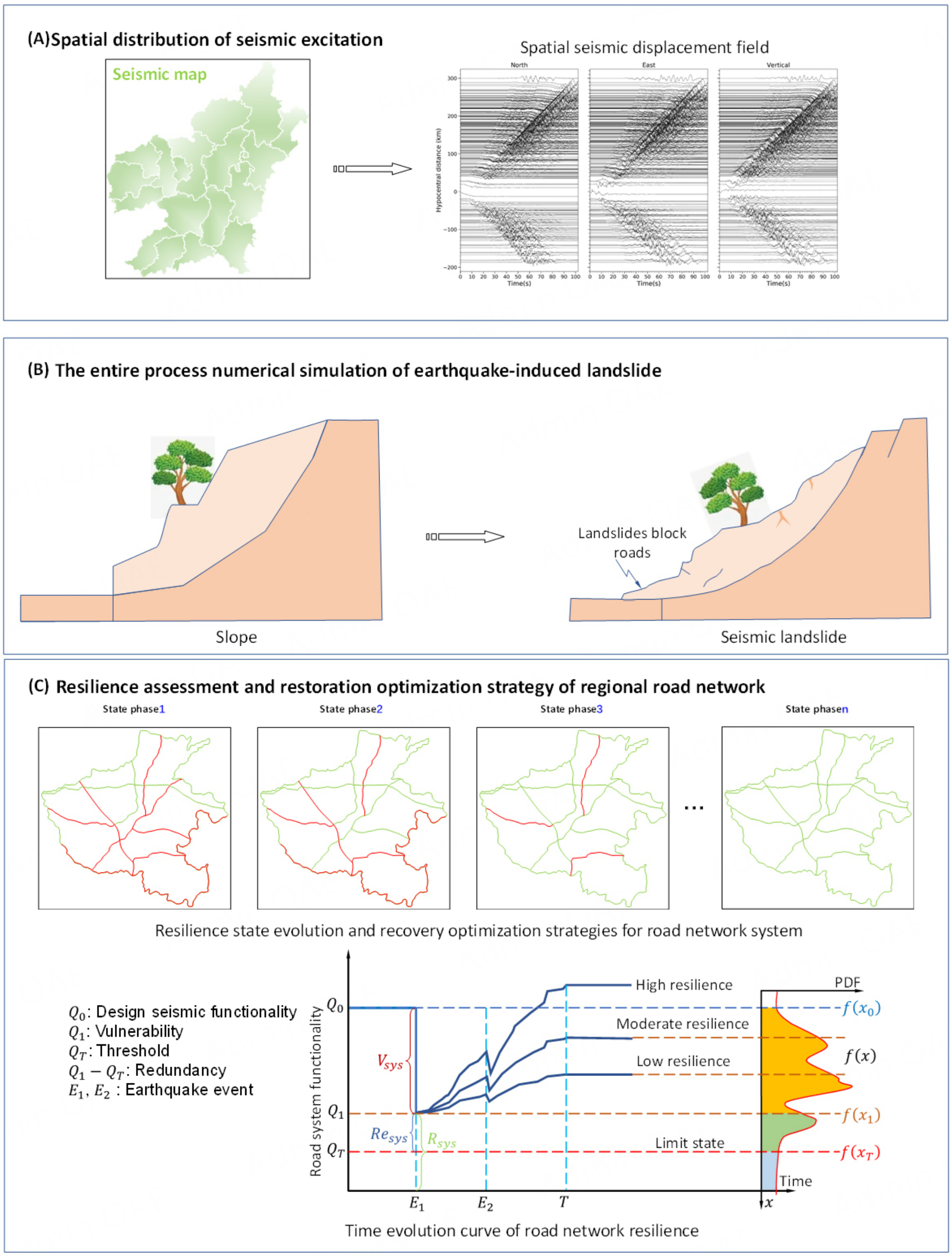

Figure 4. General workflow of the proposed resilience assessment framework for road networks.

stability performance of these slopes subjected to earthquake excitation from a reliability perspective using nonlinear dynamic time history methods based on physical mechanisms and the impact of landslide disasters on the road network. These processes inevitably involve a huge amount of computation, which can be very time-consuming. In order to improve computational efficiency, the seismic dynamic safety assessment of a large number of slopes and the numerical analysis involved in their interaction with the road network can be predicted through deep learning or transfer learning approach and codes developed by our research group. Previous studies have shown that this method can replace most nonlinear numerical calculations and effectively improve computational efficiency[45].

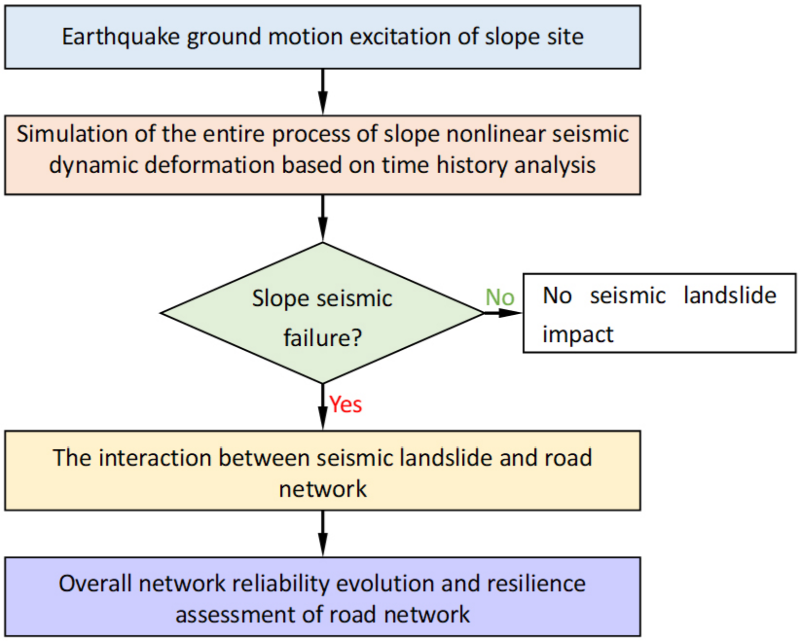

Figure 5. The flow chart for seismic resilience assessment of regional road networks

Spatiotemporal evolution of regional seismic excitation field and multi-disaster environmental excitations

Whether it is the seismic resilience of slope engineering or the resilience of regional infrastructure that resists seismic and landslide dynamic impacts after the slope transforms from a disaster-bearing body to a landslide-inducing body, the selection or modeling characterization of regional seismic excitation is a very important prerequisite. Particularly, the above-mentioned simulation-based resilience assessment methods generally involve stochastic seismic motion models in hypothetical scenarios. Additionally, owing to the particular canyon terrain and deep overburden, there are many technical difficulties in the direct application of the seismic parameters traditionally defined on the bedrock surface in alpine and canyon areas. Therefore, it is important to make full use of the results of existing seismology and geophysics research on the propagation laws of earthquake sources and seismic waves in crustal media. Using numerical algorithms to directly simulate seismic wave kinetics from the source to the slope engineering site or regional infrastructure site and determining the spatial distribution of seismic excitation can significantly improve the seismic resistance of slope engineering and the resilience evaluation level of regional infrastructure against seismic dynamic landslide impact, which is also a topic that requires in-depth investigations.

For the resilience assessment of regional road networks under earthquake-induced landslides, the first thing to be determined is the seismic excitation of the regional slope engineering site. Presently, the selection methods of seismic motion mainly include the following categories: (1) blindly selecting the strong earthquake observation records of famous earthquakes; (2) selecting the recommended response spectrum according to the seismic design specifications; (3) selecting based on the strong earthquake observation record set; (4) selecting the most unfavorable seismic motion based on the potential damage caused by the ground motion; and (5) selecting by matching and adjusting the target spectrum (frequency and intensity). However, as shown in Figure 6, there is spatial variability and spatiotemporal correlation in regional seismic motion. Therefore, the above-mentioned seismic motion selection methods are often inapplicable, and it is necessary to use methods for the artificial synthesis of seismic motion. Although many such methods exist, they mainly include the site mechanism and source mechanism, which are not detailed here. However, the

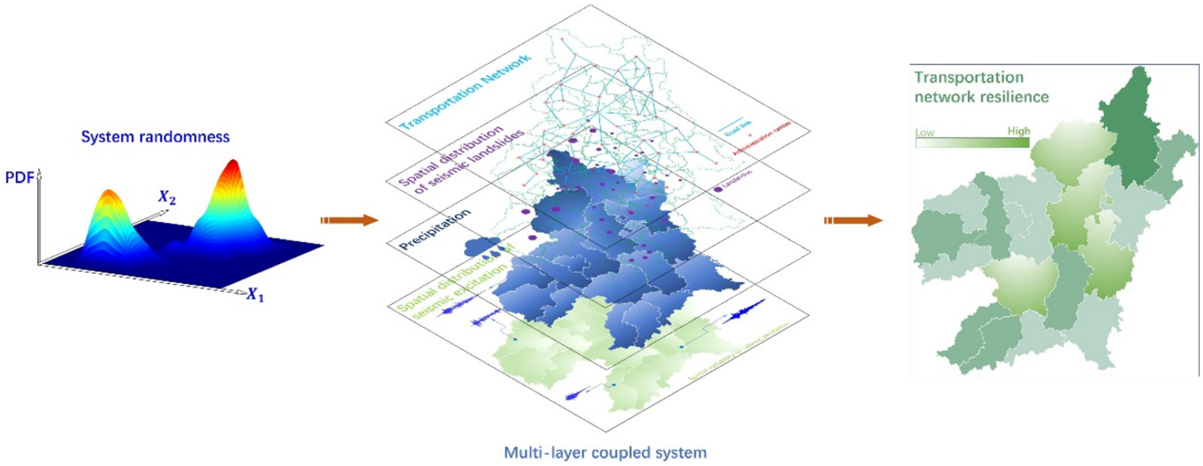

Figure 6. Coupling analysis of transportation network infrastructure systems under dynamic impact of seismic landslide disasters.

seismic excitation for regional resilience assessment should have the following characteristics: (1) theoretic soundness and algorithmic simplicity; (2) probability completeness; (3) reflects the engineering characteristics of ground motion (amplitude, duration, and frequency spectrum); (4) engineering applicability: the number of representative time courses should be appropriate; (5) the identification of model parameters complies with current seismic specifications; and (6) reflects organic integration with the latest achievements in stochastic dynamics theory. The above-mentioned factors should be considered in the artificial simulation of ground motion. As shown in Figure 6, precipitation is also an important factor contributing to regional landslides. Therefore, it is necessary to consider the correlation between the spatiotemporal distribution of rainfall and its coupling with multiple disasters, including earthquakes. Here, the temporal evolution of seismic motion involves two aspects. One key indicator is the recurrence period of strong earthquakes. Another key indicator is the duration of seismic excitation, which is not only related to the intensity of the earthquake, but generally speaking, larger earthquakes release more energy, and the process of releasing energy is also longer. Moreover, the influence of earthquake excitation duration on geotechnical materials is very significant, especially the seismic performance of slopes on liquefaction sites is highly correlated with earthquake excitation duration.

Efficient analysis method for seismic dynamic safety of road networks

Figure 4 shows the global resilience analysis process of the traffic network based on probability under multi-disaster-induced landslide impact. This process is used to analyze the function evolution of the physical system that obtains the disaster response characteristics of the regional transportation network and involves the following aspects:

(1) During the analysis process, it is necessary to consider the randomness and spatial correlation of disaster intensity (landslide impacts caused by ground motion and precipitation) and seismic dynamic response of slope engineering.

(2) A "systematic" approach should be used to investigate the critical, spanning, and cascading effects between transportation networks.

(3) By optimizing algorithms for reliability allocation, quantitative prediction can be achieved based on global reliability recovery, and the optimal recovery strategy can be determined.

The connectivity and global service reliability of road networks in mountainous areas are affected by seismic landslide disasters. Particularly, regional-scale landslide dynamic impact disasters caused by earthquakes can wash out and block roads, severely affecting the overall connectivity of the road network and posing an enormous challenge to subsequent earthquake relief and post-disaster reconstruction and recovery.

For regional road infrastructure (such as highways or railway networks) under the dynamic impact of earthquake-induced landslides, the road network system is a complex structure consisting of numerous interconnected elements, with each element forming weighted directed interaction relationships, and is controlled by a large number of parameters, whose states cannot be described solely by multi-dimensional equations but rather by coupled nonlinear dynamic equations in the form of networks to capture the interaction between system elements and reveal the complex interactions between system dynamics and underlying network topology changes. Therefore, the obtained resilience function represents a multi-dimensional manifold in the complex parameter space of the system. To extend multi-dimensional system resilience to network resilience, it is necessary to understand and investigate the following aspects: on the one hand, slope stability, that is, the nonlinear dynamic reliability of the slope, is transmitted to the reliability of road connectivity; on the other hand, the road network is based on the network reliability of graph theory. In fact, the system resilience assessment of road networks under earthquake-triggered landslide disasters starts from the analysis of seismic dynamic stability performance of slopes. For individual slopes, the seismic dynamic safety assessment considers the geometric and topological characteristics of the slope itself, the nonlinearity of geotechnical materials, joint fissures, and the potential seismic potential of regional faults. Moreover, due to the complex external natural environment in which the slope is located, the deterioration process of the geotechnical materials of a slope over time will affect its long-term seismic performance, thereby affecting the disaster resilience of the entire regional road network. Therefore, for the seismic safety assessment of slopes, it is necessary to consider the influence of multiple geological factors mentioned above and adopt a nonlinear whole process numerical simulation method based on physical mechanisms.

For the transportation network system, $S = \{V, E\}$, where V is the regional administrative center, and E is the connecting road element between the two administrative centers.

$$\begin{cases} (M+\Delta M)\ddot{U}(t)+C\dot{U}(t)+f\left[U(t),\dot{U}(t)\right]=-\boldsymbol{L}\ddot{u}_g(\theta,t)+\boldsymbol{T}_F \\ \Phi(S)=A_1+\sum_{i=1}^{m_{1C}}C_iA_i+\sum_{i=m_{1C}+1}^{m_{2C}}C_iA_i+\cdots+\sum_{i=m_{(n-1)C}+1}^{m_{nC}}C_iA_i \\ R=P[\Phi(S)]=\sum_{i=1}^{m}P(L_i) \end{cases} \tag{1}$$

In Equation (1), M, C, and $f(\cdot)$ are the mass, damping matrix, and nonlinear restoring force models of individual slope engineering, respectively; $\ddot{U}(t)$, $\dot{U}(t)$, and $U(t)$ are the acceleration, velocity, and displacement of the slope, respectively; $\ddot{u}_g(\theta,t)$ is the seismic time-history excitation; $\Delta M=-S_F^T H S_F$ is the mass matrix of pore fluid, and H is the function matrix reflecting the distribution of fluid pressure; T_F is the surface force load vector; S_F is the dynamic water pressure increment matrix. And the dynamic water pressure here considers the effects of groundwater and rainfall on the seismic dynamic response and stability performance of slopes. C_iA_i is a cluster of real-time disjoint minimum paths; C_i is the coefficient after absorption and merger; A_i is the shortest path of the connected subgraph after overall sorting; m_{nC} is the number of all connected subgraphs in the system. R is the reliability of the network system connectivity. Obviously, quickly obtaining the global reliability of the road network for evaluating the resilience of road networks under earthquake-induced landslide disasters is also a direction of future research.

Optimization of regional road network recovery process

As mentioned earlier, resilience is an inherent attribute of a dynamic system that evolves over time[46]. The transportation network in mountainous areas is no exception, particularly in terms of its operational resilience under the impact of earthquake-induced landslides. In other words, regardless of whether the overall resilience of transportation networks is measured or evaluated after earthquake and landslide disasters, their resilience state will gradually recover and improve over time with emergency rescue and reconstruction after the disaster, depending on the global connectivity of the mountain road network. Obviously, the overall resilience of mountain road networks can also be quantitatively characterized through measurement and evaluation, and the resilience recovery process can be optimized and designed through optimization strategies to achieve the fastest recovery. Thus, it is obvious that evaluating the evolution of the global resilience state of mountain road networks over time after earthquake-induced landslide disasters is particularly important because it is a prerequisite for optimizing the recovery process and is currently a research hotspot and frontier in the assessment of landslide disasters caused by regional earthquakes.

To understand the evolution process of the global time-dependent resilience of a regional road network under the impact of earthquake-induced landslides, GIS remote sensing [Figure 7] can be used to identify and evaluate the overall connectivity (full functionality, poor functionality, difficult to pass (DP), road closed (RC), and extremely difficult to recover (i.e., infinitely difficult to recover (IR)) of the regional road network at different times [Figure 8] to characterize the time-varying resilience process of the regional network based on actual monitoring data. This may be one of the fastest and most accurate methods for evaluating the resilience of regional road networks at present and may become a future research and development direction. Additionally, if decision-makers intervene in different road restoration times and sequences in the regional transportation network through optimization methods, they can maximize the restoration or improvement of the global connectivity of the regional road network within the same time frame and with limited disaster relief resources. As mentioned earlier, this global connectivity can also be characterized by the global reliability of the transportation network. Thus, the optimization problem of network reliability allocation can be solved.

Undoubtedly, it is a very complex process, from the reliability evaluation of seismic dynamic stability of slope engineering to the dynamic interaction between landslide disasters and road networks after instability. It may involve the development and propagation of random factors and the selection of different physical state indicators. Therefore, the quantitative indicators for evaluating the various states of the road in Figure 8 above should also be selected based on the seismic stability state of the slope. If the slope is stable or partially unstable under earthquake action, the state of the road may be safe (Full or Poor Functionality), which can be quantitatively characterized by the seismic stability and dynamic reliability of the slope. When a landslide disaster occurs due to slope instability, it is necessary to determine the flow volume of the landslide and the dynamic interaction between the landslide and the road network based on the aforementioned large deformation numerical analysis method. At this time, the remaining three states (DP, RC, or IR) of the road can be quantitatively determined based on the landslide accumulation volume and impact force. In the particular external environment of seismic dynamic excitation, the stochasticity (intensity and frequency) and spatial variability of seismic excitation are generally greater than the uncertainty of slope geomaterials. Moreover, owing to the spatial correlation of seismic ground motion, the failure correlation between various elements (roads) in the network cannot be ignored. Therefore, increasing redundant reserves (such as parallel elements) to improve the seismic reliability of the network system may be ineffective, increases the maintenance cost of the reserve elements, and may even lead to a decrease in the seismic reliability of the transportation network owing to the failure of reserve elements[47].

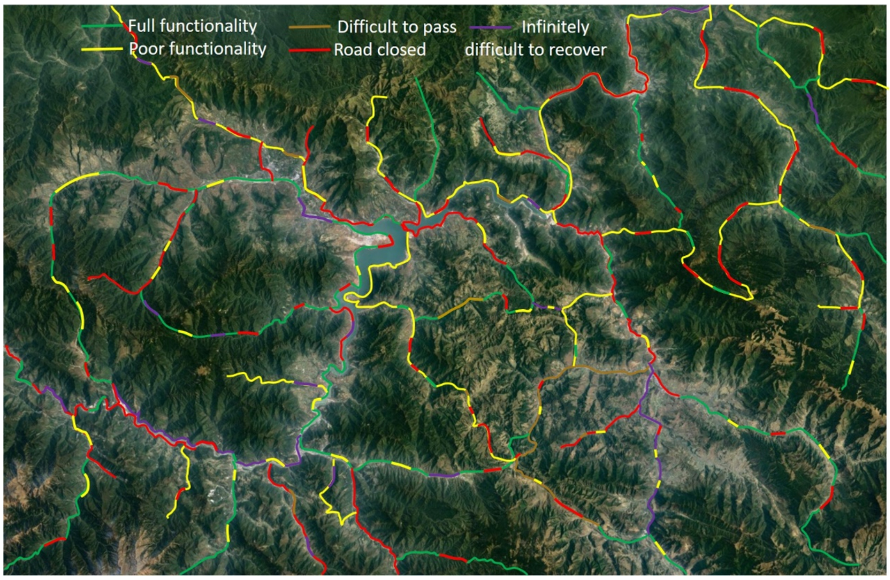

Figure 7. Road network connectivity status of earthquake-induced landslide disasters based on ArcGIS representation.

Functionality States			Blocked States	Connectivity Availability	Road Repair Classes (RC)& Specific Repair Items	
5	FF	Fully Functionality	None	All available	N/A	
4	PF	Poor Functionality	Minor landslide block	Critical ones available	Repair Class 4(RC4)	The road is blocked, but it is easier to clear.
3	DP	Difficult to pass	Minor to moderate landslide block	Unavailable	Repair Class 3(RC3)	The road is partially blocked.
2	RC	Road closed	Key road node closure	N/A	Repair Class 2(RC2)	The road is partially blocked or destroyed by landslides.
1	IR	Infinitely difficult to recover	Key nodes are severely blocked and damaged.	N/A	Repair Class 1(RC1)	The road is blocked or washed away by a landslide.

Figure 8. Functionality states of regional road networks subjected to the impact of earthquake-induced landslide disasters.

Therefore, for regional transportation networks under the potential threat of dynamic impact caused by earthquake-induced landslides, it is generally necessary to increase the impact reliability of the elements of road network systems to effectively improve their global seismic resilience. In this section, to improve the resistance of regional transportation networks to earthquake and landslide impact, under the premise of a certain post-disaster reinforcement cost and system reliability gain, the reliability increment (or reinforcement cost) of the transportation network system elements and improved elements that require post-disaster reinforcement improvement is optimized and determined to maximize the global reliability gain of the road network system or minimize the reinforcement cost. In the optimization of the post-disaster recovery process of the road network system, the first step is to determine the probability importance and unit sensitivity of the road network system elements. Generally, the importance of the road network system elements does not only depend on the logical structure of the elements but also depends on the reliability of each unit and the reliability of the road network system as a whole.

If the reliability of the i-th unit of the road network system S is denoted as p_i, the global system reliability R_S of the road network system can be expressed as follows:

$$R_S = R_S(p_1, p_2, \cdots, p_n) \tag{2}$$

Then, the sensitivity of the i-th unit can be defined as follows:

$$\frac{\partial R_S}{\partial p_i} = \frac{\partial R_S(p_1, p_2, \cdots, p_n)}{\partial p_i} \tag{3}$$

Obviously, as the value of $I_{\text{prob},i} = \frac{\partial R_S}{\partial p_i}$ increases, the sensitivity of the i-th road element becomes higher; that is, the improvement of unit reliability p_i has a greater gain on the global system reliability R_S of the road network. As can be seen, the sensitivity and probability importance $I_{\text{prob},i}$ of the road network elements are the same concept, and the probability importance becomes higher as the sensitivity increases.

In the optimization of road network design for earthquake and landslide impact resistance, the main optimization objectives are the global system reliability, total cost, total loss expectation, and total investment of the road network system. Presently, the functional relationship between the cost C of the road network system and the system reliability R_S has not been established; therefore, the decision-making analysis of the global system reliability of the road network system can only be carried out from the perspective of element reliability. For a regional transportation network affected by earthquake-induced landslide disasters, the total investment W_0 in post-disaster recovery corresponds to a certain amount. Under this constraint, the optimization and coordination of the reliability $p_i(i \in V$ or $i \in E)$ characterizing the connectivity of each road to maximize the disaster resistance reliability R_S of system S is achieved by finding the reliability vector $\boldsymbol{p}$ of each road element that maximizes the global disaster resistance system reliability of the transportation network system. The specific mathematical expression can be written as follows:

$$\begin{cases} \boldsymbol{p} = p\left(p_1, p_2, \cdots, p_i, \cdots, p_{|V|+|E|}\right) \\ R_S(\boldsymbol{p}) \to \max \\ s.t.\ \ C_T C_0(\boldsymbol{p}) + M(\boldsymbol{p}) - B(\boldsymbol{p}) R_S = W_0 \end{cases} \tag{4}$$

where T represents the service period of the regional road infrastructure; $B(\boldsymbol{p})$ represents the economic benefits generated by system S during the service period T; $B(\boldsymbol{p})R_S$ represents the expected value of economic benefits; C_0 is the initial cost, and C_T is the fluctuation of the initial cost under the combined influence of price and bank interest rate fluctuations during the service period T. Obviously, Equation (4) is a nonlinear programming problem with equality and can be solved using the Lagrange multiplier method[48].

$$p_i = 1 - \frac{\beta_i C_T}{\alpha_i\left[D_i + \left(B + \frac{1}{\lambda}\right) I_{prob,i}\right]}, \tag{5}$$

where β_i is the basic cost of the road unit when considering the impact of landslide disasters; α_i is the projection coefficient describing the cost and connectivity reliability of the road element; D_i is the loss caused by the landslide failure of the road; λ is the Lagrange multiplier.

However, the difficulty here still lies in obtaining the global system reliability R_S of the regional transportation network under the impact of earthquake-induced landslide disasters. As mentioned above, in the existing literature, the overall reliability analysis of complex network systems is mostly proven using an exhaustion or simulation method. Notably, these methods may be more suitable for small-scale networks but are often inadequate for large and complex traffic networks. Therefore, the authors propose using non-simulation methods that are suitable for assessing the network reliability, such as the recursive decomposition algorithm[49].

In Figure 9, the red line indicates roads that have been blocked or destroyed after landslide impact, while the green line indicates that the passing roads are in good condition. This figure is a schematic diagram of the restoration process of the road network after an earthquake-triggered landslide disaster impact. It is a part of the evaluation framework for seismic resilience of road networks proposed in this study. For actual post-earthquake recovery, the funding for rescue is always limited, and it may not be possible to quickly restore the entire regional road network. So, under the constraint of limited funds, how to maximize the rapid recovery of road network functions, that is, the order of road network recovery, is determined by the optimization strategy calculation of Equation (4) mentioned earlier. According to different repair sequences, the connectivity of the road network units is gradually restored, resulting in the gradual restoration of the functionality of the entire road network system. The specific repair state evolution is shown in Figure 8. Based on the optimized allocation of reliability among various road elements in the road network system, the recovery time of the road network after landslide disasters can be optimized and determined.

In the post-disaster recovery process of infrastructure systems, there is a mutual relationship in multi-layer networks, that is, the interdependence caused by the recovery process. This is called recovery coupling and is different from multi-layer cascading failures, which have been extensively investigated owing to their particular characteristics and dynamics and interdependent networks with hard coupling. For example, as shown in Figure 10, a road blockage caused by an earthquake may not result in a power outage but may delay power restoration in the affected area. Obviously, large-scale power outages caused by the earthquake-induced failure of regional power grids will also slow down the rapid connection of regional roads to some extent. In other words, after large-scale disturbances, the recovery process of different network systems exhibits coupled nonlinear behavior. Currently, there is little research on the recovery coupling relationship in multi-layer networks, and this may be a future research direction for evaluating the resilience of regional road networks to earthquake-induced landslide disasters[50].

CONCLUSIONS

This study systematically reviewed the development and evolution of slope engineering seismic resilience, from the engineering seismic resilience of a single slope to the resilience of regional road networks against earthquake-induced landslide disasters. The specific conclusions drawn from this study are as follows:

(1) Slopes are not completely similar to other superstructure projects. This study proposes a new definition of seismic resilience for slope engineering. Before an engineered slope undergoes instability and forms a landslide under earthquake action, its seismic resilience mainly includes seismic robustness and recoverability, similar to other building structures. When a slope loses stability and a landslide occurs, its resilience should be described as the anti-disaster resilience of the regional road network affected by earthquake-induced landslide disasters.

(2) Currently, research on the seismic resilience of slopes mainly focuses on slope engineering; that is, the stage before the slope becomes unstable by earthquakes and transforms into a landslide disaster. However,

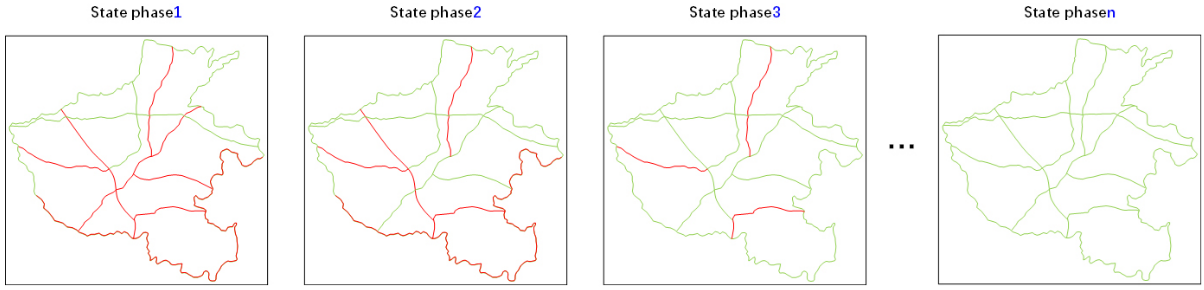

Figure 9. Evolution process of functional state recovery of regional road networks after landslide disasters.

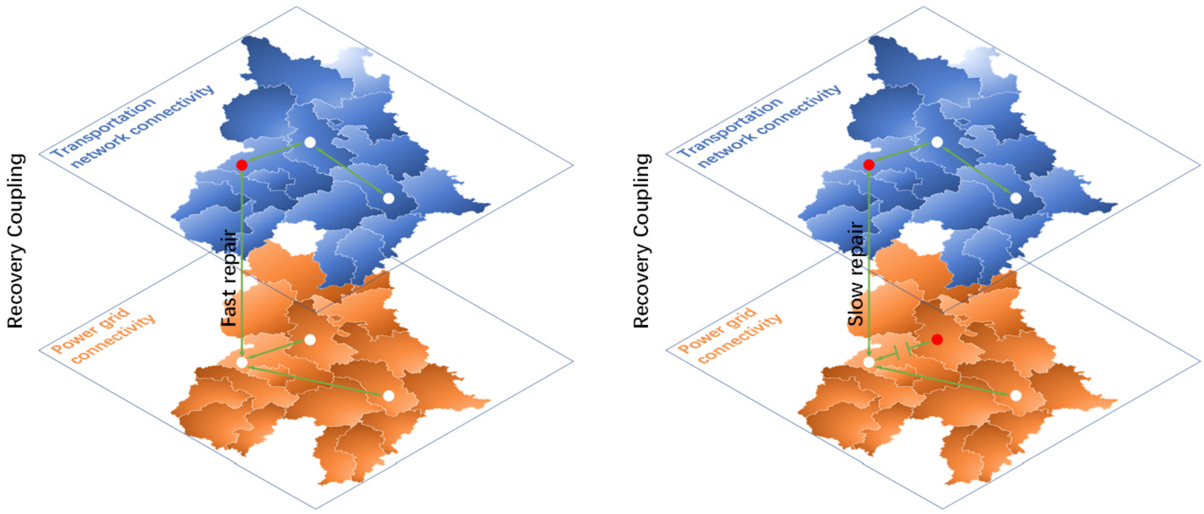

Figure 10. Recovery coupling caused by interdependence in the recovery process.

there is very little research on the resilience of regional road networks affected by earthquake-induced landslide disasters. The main reasons for this are the spatial distribution of seismic excitation and the constraints on how the resilience of regional road networks is characterized and calculated. More research should be conducted on the resilience of road networks in areas affected by earthquake-induced landslide disasters.

(3) A resilience assessment framework for road networks has been preliminarily established, and future research directions, such as modeling the regional seismic excitation, characterizing the regional road network resilience based on network reliability, and developing recovery optimization strategies, are proposed.

(4) The distribution of regional landslides triggered by earthquakes is influenced by the combined effects of ground motion excitation, precipitation, and other phenomena. Therefore, it is necessary to consider the combined effects of precipitation, ground motion, and other multi-disaster environmental excitations in the resistance of regional infrastructure to earthquake-induced landslide disasters. Moreover, owing to the coupling effect of other related networks on the post-disaster recovery of regional road networks, research should be carried out in the direction of nonlinear high-dimensional network dynamics.

DECLARATIONS

Authors' contributions

Methodology, writing - original draft, and visualization: Xiong M, Hu H
Conceptualization, methodology, validation, formal analysis, review & editing, resources, supervision, and project administration: Huang Y

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCES

1. Rodríguez-izquierdo E, Cid A, García-meneses PM, et al. From resilience attributes to city resilience. *Landscape Urban Plan* 2022;226:104485. DOI
2. Fisher L. Disaster responses: more than 70 ways to show resilience. *Nature* 2015;518:35. DOI PubMed
3. Cohen AA, Ferrucci L, Fülöp T, et al. A complex systems approach to aging biology. *Nat Aging* 2022;2:580-91. DOI
4. Tang WH, Yucemen MS, Ang AH. Probability-based short term design of soil slopes. *Can Geotech J* 1976;13:201-15. DOI
5. Bruneau M, Chang SE, Eguchi RT, et al. A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthq Spectra* 2003;19:733-52. DOI
6. Li J, Chen J. The principle of preservation of probability and the generalized density evolution equation. *Struct Saf* 2008;30:65-77. DOI
7. Alipour A, Shafei B. Seismic resilience of transportation networks with deteriorating components. *J Struct Eng* 2016;142:C4015015. DOI
8. Chen SC, Ferng JW, Wang YT, Wu TY, Wang JJ. Assessment of disaster resilience capacity of hillslope communities with high risk for geological hazards. *Eng Geol* 2008;98:86-101. DOI
9. Shafieezadeh A, Ivey Burden L. Scenario-based resilience assessment framework for critical infrastructure systems: case study for seismic resilience of seaports. *Reliab Eng Syst Saf* 2014;132:207-19. DOI
10. Tsompanakis Y, Lagaros ND, Psarropoulos PN, Georgopoulos EC. Probabilistic seismic slope stability assessment of geostructures. *Struct Infrastruct Eng* 2010;6:179-91. DOI
11. Hu H, Huang Y, Chen Z. Seismic fragility functions for slope stability analysis with multiple vulnerability states. *Environ Earth Sci* 2019;78:690. DOI
12. Kwag S, Hahm D, Kim M, Eem S. Development of a probabilistic seismic performance assessment model of slope using machine learning methods. *Sustainability* 2020;12:3269. DOI
13. Hu H, Huang Y, Zhao L. Probabilistic seismic-stability analysis of slopes considering the coupling effect of random ground motions and spatially-variable soil properties. *Nat Hazards Rev* 2020;21:04020028. DOI
14. Seo H, Lee YJ, Park D, Kim B. Seismic fragility assessment for cantilever retaining walls with various backfill slopes in South Korea. *Soil Dyn Earthq Eng* 2022;161:107443. DOI

15. Vecchietti A, Cecconi M, Russo G, Pane V. Seismic vulnerability of a rockfill dam through different displacement-based approaches. *J Earthq Eng* 2022;26:113-39. DOI
16. Wang W, Li DQ, Tang XS, Du W. Seismic fragility and demand hazard analyses for earth slopes incorporating soil property variability. *Soil Dyn Earthq Eng* 2023;173:108088. DOI
17. Li XY, Fan ZB, Lu T, Xiao T, Zhang LM. A resilience model for engineered slopes subject to anchor corrosion. *KSCE J Civ Eng* 2018;22:887-95. DOI
18. Huang Y, He Z. Rainfall-oriented resilient design for slope system: resilience-enhancing strategies. *Soils Found* 2023;63:101297. DOI
19. Blackman D, Nakanishi H, Benson AM. Disaster resilience as a complex problem: why linearity is not applicable for long-term recovery. *Technol Forecast Soc Chang* 2017;121:89-98. DOI
20. He Z, Huang Y, Zhao C. A preliminary general framework for seismic resilience assessment of slope engineering. *Bull Eng Geol Environ* 2022;81:463. DOI
21. Lin P, Wang N. Stochastic post-disaster functionality recovery of community building portfolios I: modeling. *Struct Saf* 2017;69:96-105. DOI
22. Hariri-ardebili MA. Risk, Reliability, Resilience (R^3) and beyond in dam engineering: a state-of-the-art review. *Int J Dis Risk Reduct* 2018;31:806-31. DOI
23. Argyroudis SA, Mitoulis SA, Winter MG, Kaynia AM. Fragility of transport assets exposed to multiple hazards: state-of-the-art review toward infrastructural resilience. *Reliab Eng Syst Saf* 2019;191:106567. DOI
24. El-maissi AM, Argyroudis SA, Nazri FM. Seismic vulnerability assessment methodologies for roadway assets and networks: a state-of-the-art review. *Sustainability* 2021;13:61. DOI
25. Taylor FE, Tarolli P, Malamud BD. Preface: landslide-transport network interactions. *Nat Hazards Earth Syst Sci* 2020;20:2585-90. DOI
26. Sidle RC, Ziegler AD. The dilemma of mountain roads. *Nat Geosci* 2012;5:437-8. DOI
27. Gupta V, Sah MP. Impact of the trans-himalayan landslide lake outburst flood (LLOF) in the satluj catchment, himachal pradesh, India. *Nat Hazards* 2008;45:379-90. DOI
28. Wu R, Zhang Y, Guo C, Yang Z, Tang J, Su F. Landslide susceptibility assessment in mountainous area: a case study of Sichuan-Tibet railway, China. *Environ Earth Sci* 2020;79:157. DOI
29. Wang X, Pan C. Review of seismic damage characteristics and influence factors of mountain tunnels. *Arab J Geosci* 2022;15:478. DOI
30. Nicolosi V, Augeri M, D'apuzzo M, Evangelisti A, Santilli D. A probabilistic approach to the evaluation of seismic resilience in road asset management. *Int J Dis Risk Sci* 2022;13:114-24. DOI
31. Ering P, Sivakumar Babu G. Effect of spatial variability of earthquake ground motions on the reliability of road system. *Soil Dyn Earthq Eng* 2020;136:106207. DOI
32. Liao T, Hu T, Ko Y. A resilience optimization model for transportation networks under disasters. *Nat Hazards* 2018;93:469-89. DOI
33. Ishibashi H, Akiyama M, Frangopol DM, Koshimura S, Kojima T, Nanami K. Framework for estimating the risk and resilience of road networks with bridges and embankments under both seismic and tsunami hazards. *Struct Infrastruct Eng* 2021;17:494-514. DOI
34. Zimmaro P, Stewart JP, Brandenberg SJ, Kwak DY, Jongejan R. Multi-hazard system reliability of flood control levees. *Soil Dyn Earthq Eng* 2019;124:345-53. DOI
35. Sarkissian R, Abdallah C, Zaninetti J, Najem S. Modelling intra-dependencies to assess road network resilience to natural hazards. *Nat Hazards* 2020;103:121-37. DOI
36. D'apuzzo M, Evangelisti A, Spacagna RL, et al. Seismic resilience assessment strategy for social and sustainability impact evaluation on transportation road network: a seismic liquefaction-induced damage application. *Sustainability* 2022;14:8411. DOI
37. Kilanitis I, Sextos A. Integrated seismic risk and resilience assessment of roadway networks in earthquake prone areas. *Bull Earthq Eng* 2019;17:181-210. DOI
38. Chen J, Pan C, Wu C, Liu WK. Reproducing kernel particle methods for large deformation analysis of non-linear structures. *Comput Methods App Mech Eng* 1996;139:195-227. DOI
39. Liu M, Liu G. Restoring particle consistency in smoothed particle hydrodynamics. *Appl Numer Math* 2006;56:19-36. DOI
40. Huang Y, Li G, Xiong M. Stochastic assessment of slope failure run-out triggered by earthquake ground motion. *Nat Hazards* 2020;101:87-102. DOI
41. Shi G, Goodman RE. Two dimensional discontinuous deformation analysis. *Num Anal Meth Geomech* 1985;9:541-56. DOI
42. Soga K, Alonso E, Yerro A, Kumar K, Bandara S. Trends in large-deformation analysis of landslide mass movements with particular emphasis on the material point method. *Géotechnique* 2016;66:248-73. DOI
43. Huang Y, Xiong M, Zhao LY. Slope stochastic dynamics. Heidelberg: Springer; 2022. DOI
44. Huang Y, Xiong M, Hu HH. Guidelines for probabilistic performance-based seismic design and assessment of slope engineering. Heidelberg: Springer; 2023. DOI
45. Huang Y, Han X, Zhao L. Recurrent neural networks for complicated seismic dynamic response prediction of a slope system. *Eng Geol* 2021;289:106198. DOI
46. Liu X, Li D, Ma M, Szymanski BK, Stanley HE, Gao J. Network resilience. *Phys Rep* 2022;971:1-108. DOI
47. Moses F. New directions and research needs in system reliability research. *Struct Saf* 1990;7:93-100. DOI
48. Li GQ, Huo D, Wang DW. Seismic reliability analysis of urban building network system. Beijing: Seismological Press; 1993.

49. Lim H, Song J. Efficient risk assessment of lifeline networks under spatially correlated ground motions using selective recursive decomposition algorithm. *Earthq Engng Struct Dyn* 2012;41:1861-82. DOI

50. Danziger MM, Barabási AL. Recovery coupling in multilayer networks. *Nat Commun* 2022;13:955. DOI PubMed PMC