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Original Article

Emergency road network structure and planning optimization in mountainous regions in Southwest China under earthquake scenarios

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Abstract: Emergency road networks (ERNs), an important part of local disaster prevention systems, can provide security to residents and their property. Exploring the ERNs structure is of great significance in terms of promoting disaster prevention and establishing road safety in dangerous mountainous areas. This study considered the ERNs of the Kangding section of the Dadu River Basin as the area for a case study. Complex Network Analysis was used to examine the relationship between the four characteristic indicators of mountain roads and the degree of earthquake impacts under the Lushan, Wenchuan, and Kangding Earthquake scenarios. Based on the analysis results, the southwest mountain road network was evaluated; then, computer simulations were used to evaluate the structural changes in the road network after index changes. The network was optimized, and the corresponding emergency avoidance network was proposed to provide a reference for the establishment of the mountainous ERN. The results show that the overall completeness of the mountainous ERNs in Southwest China is poor and prone to traffic accidents. Moreover, the local stability is poor, and the network is susceptible to natural hazards. The overall structure of the road network is balanced, but that of certain road sections is not. Road sections with different attributes present a "gathering-scattering" spatial distribution, i.e, some sections are clustered together while others are far apart. Accordingly, a planning optimization strategy is proposed to better understand the complexity and systematic nature of the mountainous ERN as a whole and to provide a reference for disaster prevention and mitigation planning in mountainous regions in Southwest China.

Keywords: Southwest China; Emergency road network; Mountainous area; Complex Network Analysis; Structural characteristics; Geological hazards

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1 Introduction

In recent years, natural disasters, such as the Wenchuan Earthquake (2008), Yushu Earthquake (2010), Zhouqu Mudslide (2010), Ya'an Earthquake (2013), and Lushan Earthquake (2014), have frequently occurred in the southwestern mountainous areas of China, leading to significant casualties in a short time, urban infrastructure damage, and economic losses and impacting the recovery of affected areas and their long-term development. In addition, rapid urbanization has brought about a variety of risks, which have drawn wide attention to research on regional emergency rescue road networks.

An emergency rescue network is a complex system that plays an important role in disaster prevention and mitigation. The conditions of the network structure have an important impact on rescue efficiency. Accordingly, improving the performance of such networks is a research priority (Leng et al. 2017; Yucel et al. 2018). Presently, two common definitions are used to define an emergency rescue network: (1) a network comprising the various organizations participating in rescue efforts and the logistics network created by relevant emergency supplies (Huang and Song 2018) and (2) an important lifeline or emergency evacuation route following a natural disaster, especially an earthquake (Wang and Wang 2018). However, in the mountainous areas in Southwest China, because of the complex terrain, the mountain road networks are mostly branch-shaped or chain-shaped, which is inconvenient and vulnerable to traffic accidents. Moreover, due to the frequency and uncertainty of mountain disasters, it is impossible to plan emergency evacuation routes that are as good as those in cities, which makes it extremely difficult to improve evacuation following an earthquake. This paper argues that, in the case of the mountainous ERN in Southwest China, the components should include network and emergency refuge facilities, and an in-depth understanding of the characteristics of the mountain road network structure is necessary. Accordingly, a corresponding road network plan should be proposed to strengthen the emergency shelter space planning strategy to implement a "priority to prevention" approach instead of a "priority to evacuation" approach.

The international community recognizes the importance of identifying the structural characteristics of ERNs (Soltani-Sobh et al. 2016; Kaviani et al. 2018) and has begun preliminary exploration of road planning, construction, and management methods by focusing on the following aspects. (1) Post-disaster ERN reliability and vulnerability: Japanese scholars have investigated road and traffic facilities in an earthquake zone after analysing the damage caused by the Kobe Earthquake in 1995 (Menoni et al. 2001). Scholars have proposed an algorithm to describe the network connectivity reliability of road network performance (Ball et al. 1979). Bell et al. (2000) applied game theory to analyse the reliability of transport networks. Chen et al. (2002) proposed the road network capacity reliability index, which indicates the probability that a road network can accommodate the expected traffic demand. Various assessment methods have been proposed to evaluate the structure of road networks and their reliability (Zio et al. 2011; Kroes et al. 2017), as well as road network optimization (Mooselu et al. 2020). (2) Post-disaster emergency network simulation: the transit networks of London and Paris have been analysed to determine the impact of a random failure or attack on public transit networks. The results showed that a small amount of damage to the structure of a road network could lead to network paralysis (Von et al. 2012). Zhang et al. (2016) extracted hub networks from urban rail transit networks and analysed their characteristics. The robustness, criticality, and complexity of transit networks against disasters have also been evaluated through simulations and case studies (Yang et al. 2015; Yang et al. 2018; Derrible et al. 2012). (3) Emergency response: a clustering-optimization approach (Zhang et al. 2006) and a mathematical model (Benrhaiem et al. 2019) have been proposed to facilitate the distribution of emergency relief after disasters. (4) Site selection and the allocation of emergency service resources and other emergency logistics: Liu et al. (2012) used the case-based reasoning method to predict emergency resource demand, providing a basis for the allocation of emergency relief. Sarma et al. (2020) attempted to optimize the distribution of traffic in road networks to improve emergency resource allocation. Other studies have conducted spatial evaluations to review the location of emergency resources (Kato et al. 2020; Manfre et al. 2020).

The abovementioned studies provide a rich and useful reference; however, the following issues remain. First, in terms of research content, most previous studies have been simulation-based, but analyses of the correlations among factors in real-world scenarios are rare. Additionally, more attention has been given to post-disaster evacuation than to pre-disaster prevention. Second, in terms of research methods, compared with geographic information system analysis and mathematical model analysis, fewer studies have used Complex Network Analysis methods, and there is a lack of focus on the spatial significance and influencing factors reflected by network structures. Third, in terms of scope, previous research on ERNs has focused primarily on large cities, such as Beijing and Shanghai, and flatlands; studies involving mountainous areas are rare. Therefore, to facilitate sustainable development of mountainous disaster-prone areas, this study used Complex Network Analysis and computer simulation to study the ERN in the Kangding section of the Dadu River Basin. Objectives, starting from the characteristics of the complex network structure of the ERN, were combined with specific cases in mountainous disaster-prone areas to quantitatively evaluate and analyse the network density, K-core, Close-to-the-centre potential, Degree centre potential, etc. of the emergency rescue road network under realistic disaster scenarios. Furthermore, an in-depth interpretation of the meaning of the index planning and structural characteristics of the ERN was obtained. Recommendations for the construction and management of an emergency rescue road network after a disaster are provided.

2 Study Area and Data Sources

Currently, many areas on Earth face increasingly serious practical problems: geological disasters frequently occur, and emergency rescue systems often fail to perform well, resulting in serious economic and social losses. The purpose of this paper is to alleviate such problems and to serve as a reference for the planning of emergency rescue road networks in mountain disaster areas.

The mountainous region in Southwest China is one of the country's most disaster-prone areas. To better discuss the topological structural mechanism and evolutionary characteristics of the ERN in this region as part of a multi-disaster scenario, regions with mountainous roads in Southwest China and their natural and economic conditions were selected for this study. The study area covers approximately 3113 square kilometres, including towns of Guzan and Jintang, and townships of Shiji, Yutong, Maibeng, Sanhe, Pengta, and Kongyu. The permanent population is 43,000. From the perspective of the overall landform distribution in China, the Dadu River Basin in Kangding City is located in the Hengduan Mountains between the Daxue and Qionglai mountain ranges. It is the transition zone between the first and second steps of the Qinghai-Tibet Plateau. It is affected by the sharp uplift of the Qinghai-Tibet Plateau and river cutting. The high mountains and valleys in the territory are staggered. There are 4 high mountains with an altitude of more than 5000 meters, including the Cedar (5016 meters), and the mountains are generally high in the west and low in the east. The topography and landforms are complex, and there is a combination of basins and plateaus in the landscape.

The Kangding section of the Dadu River Basin has long suffered from natural disasters such as debris flow and collapse. The region experiences the following practical problems: (1) the road network is extremely vulnerable to failure in the case of disasters and does not meet the requirements for rapid post-disaster rescue and evacuation; and (2) the spatial layout of emergency shelter facilities does not meet the needs of local people requiring shelter following a disaster. Therefore, this area was selected as the study area (Fig. 1). The data in this study were derived from a field investigation (the research team conducted a field survey in this research area for half a year during2018-2019 and obtained a large quantity of first-hand data), government sources (geological disaster investigation report and government report of Ganzi Prefecture, China), remote sensing images (GIS platform acquisition), and the status quo of emergency shelter facilities (Fig. 2). The level-I shelter facilities have a larger service scope and are more developed than level-II shelter facilities. Sections damaged by the Lushan, Wenchuan, and Kangding earthquakes are marked in Fig. 3.

Source: Image based on the "Results Report of the 2017 Kangding City of Ganzi Prefecture on the Investigation of Potential Geological Hazards (2017)".

3 Methodology

The existing ERN system was transformed into a

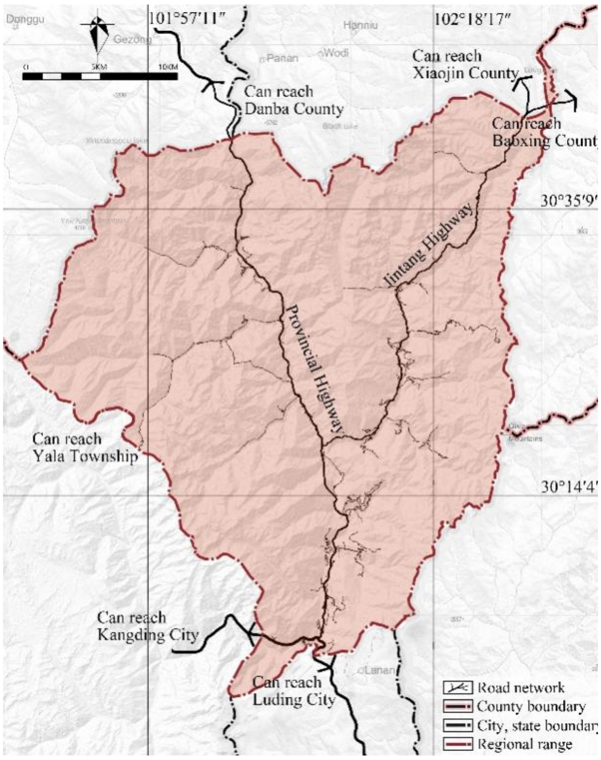

Fig. 1 Study area: the Dadu River Basin in Kangding City, Ganzi Prefecture, Sichuan Province, China.

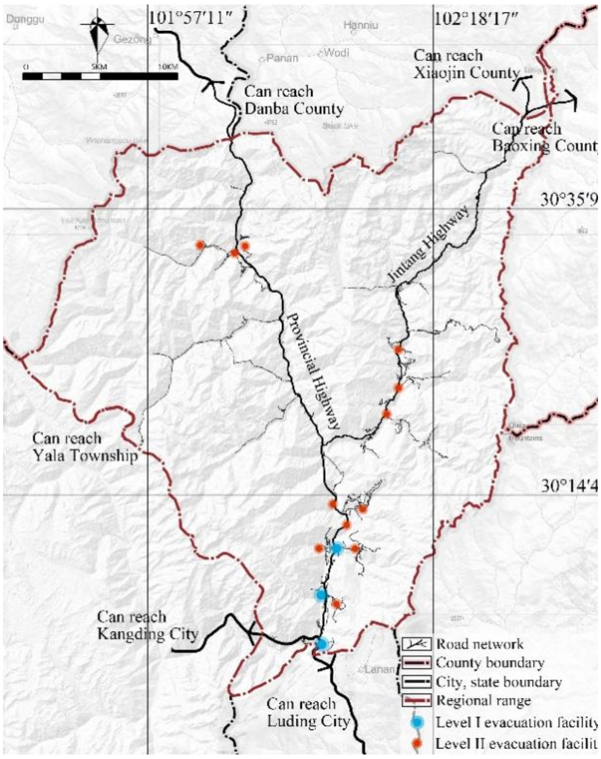

Fig. 2 Current situation of emergency shelter facilities in the study area.

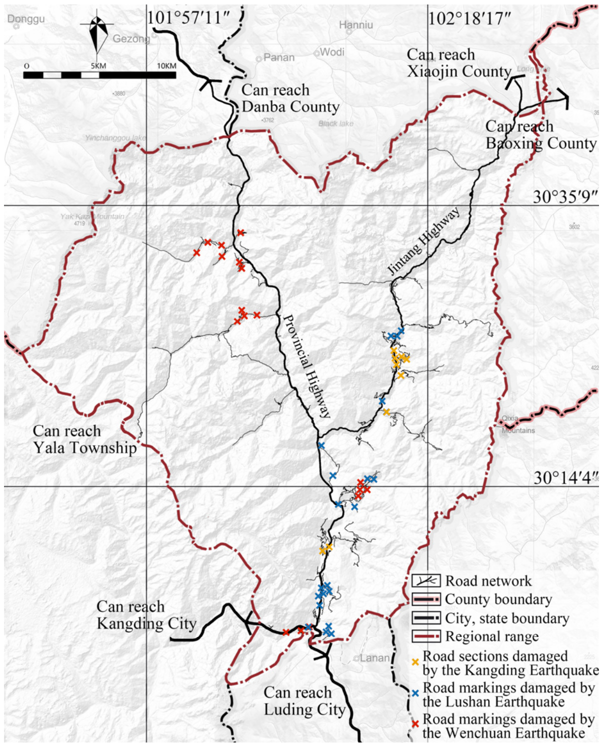

Fig. 3 Road sections damaged by different earthquakes. The markings on the picture are road sections damaged by the earthquake.

network model, and an evaluation index system for typical ERN structures was established. The topological structural mechanism of an ERN was explored within a real disaster scenario, and corresponding planning and response strategies were proposed.

The overall technical approach was divided into three steps. The first step required determining the geospatial location of road sections and gathering relevant data through an investigation and analysis of the research area, thus enabling the creation of a complex network model representing an emergency network using the Pajek software platform. In the second step, complex network theory analysis and a computer simulation were used to evaluate a real disaster scenario to better understand the structural completeness, structural stability, and structural balance of the network. The third step compared and analysed data, revealed the patterns, and provided planning strategies for ERN construction and management in mountainous areas.

3.1 Semantid characteristics of the Complex Network Semantic Model

In this study, map modelling was conducted according to the relationship between road intersections and road segments. The road sections were taken as points, and intersections represented the edges of the network. This method can be applied to complex road networks to reflect the topological characteristics of the network and to identify the importance and correlation of network edges and nodes. In addition, the actual length of the network can be ignored. By performing semantic transformation of the real road system on several roads between adjacent intersections or towns and villages (road sections between two points were numbered, and a road section in a complex network was considered to be a network node), a total of 251 nodes were derived. Among them, 30 were emergency refuge nodes (that is, road edges with current emergency shelters), The intersections between road segments were denoted as lines, for a total of 599 edges, to establish a realistic system.

3.2 Evaluation index system

This study aimed to evaluate the completeness, stability, and balance of ERNs via complex network theory. The “network density” index was used to measure the completeness of the road network, the "K-core" index was used to measure the stability of the network, and the trends of "Close-to-the-centre potential" and "Degree centre potential" were used to measure network balance (Choi et al. 2010). These four metrics were adopted to assess the road network under the realistic scenarios of the Lushan, Wenchuan, and Kangding earthquakes.

3.2.1 Network density

The overall completeness of the network was determined by measuring the network density using the following formula:

$$P = L/[\frac{n(n-1)}{2}] \quad (1),$$

where P is the network density, L is the number of connections present in the network, and n is the number of nodes present in the network.

3.2.2 K-core

K-core (K = 1, 2, 3...) represents all points in a subgraph connected to at least "K" other points in the same sub-graph. Therefore, the higher the value of K is and the higher the proportion of K-core is, the more stable the network will be overall.

3.2.3 Close-to-the-centre potential

The close-to-the-centre potential measures the extent to which a node is "in the middle" of any two other nodes. A high close-to-the-centre potential means that a node is located in a more central position of the network. The formula for deriving this value is as follows:

$$N = \frac{\sum_{i=1}^{n}(N_{RBmax} - N_{RBi})}{n-1} \quad (2),$$

where N_{RBmax} is the theoretical maximum absolute centre of the point, N_{RBi} is the absolute intermediate centre of the point, and N is the relative centre of the point.

3.2.4 Degree centre potential

The degree centre potential can be used to evaluate the overall centrality of a network and to assess the overall equilibrium degree and central tendency of each section of a traffic network. The formula for deriving this indicator is as follows:

$$C = \frac{\sum_{i=1}^{n}(C_{max} - C_i)}{max[\sum_{i=1}^{n} C_{max} - C_i]} \quad (3),$$

where C is the degree centre potential, and C_{max} is the maximum value of the central degree of each node in the network, and C_i is the degree centrality of node i.

4 Calculation Results and Analysis

A comparative analysis of the road network attribute evaluation under different earthquake scenarios is shown in Fig. 4. Meanwhile, the calculation results of different indicators are explained in the following subsections.

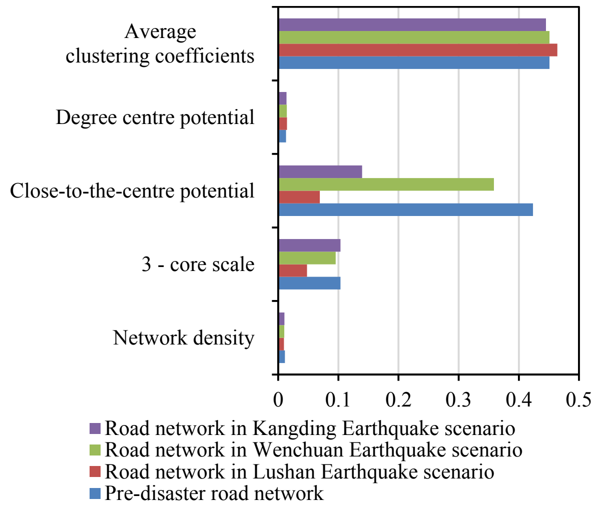

Fig. 4 Network attribute evaluation under different earthquake scenarios.

4.1 Network density

In graph theory, density describes the closeness of points in a graph. The network density is the ratio of the number of connections actually presented in a graph to the maximum number of connections that may be available. In terms of the density of the road network, the studied scenarios were ranked as follows: the pre-disaster scenario > the Kangding Earthquake scenario > the Wenchuan Earthquake scenario > the Lushan Earthquake scenario. The Lushan Earthquake scenario had the lowest road network density; as such, its network completeness was the lowest: 31 traffic islands formed because of the Lushan Earthquake, and six emergency shelters were isolated. Only self-rescue could be completed in this case. Two emergency shelters could service only three traffic nodes, and the distribution of shelters was relatively uneven. The rescue network for the magnitude 6.3 Kangding Earthquake had a high degree of completeness and formed 16 traffic islands. Three emergency shelters were isolated and had no rescue effect, two emergency shelters could service only two traffic nodes, and the other shelters were evenly distributed. Thus, the network was able to effectively complete post-disaster relief work. Following the Wenchuan Earthquake, 26 traffic islands formed, and one emergency shelter was isolated; the remaining shelters could effectively complete post-disaster relief work. The lower the network density index is, the more likely it is for traffic islands to occur.

4.2 K-core

The K-core calculations on the normal and post-disaster scenario networks indicated that the maximal K-core distributions in the network structures were 3-core and 2-core, respectively. Under the Kangding Earthquake scenario, the 2-core accounted for 60.56%, and the 3-core accounted for 10.36%, showing high stability than other scenarios. Therefore, in terms of the stability of the road network, the order was the pre-disaster scenario > the Kangding Earthquake scenario > the Wenchuan Earthquake scenario > the Lushan Earthquake scenario. The calculation results show that the local stability of the road network under the Kangding Earthquake was relatively high. There were 74 nodes in the 1-core and 0-core scenarios; among these, as well as emergency shelters 37, 127, and 146, were isolated. Therefore, the shelters and road systems connected to those shelters required strengthening. The Wenchuan Earthquake had a weak impact on the stability of the road network structure. There were 84 nodes in the 1-core and 0-core scenarios, and emergency shelter No. 220 was isolated and therefore required strengthening. The local stability of the ERN in the Lushan Earthquake scenario was extremely poor: 88 nodes were present in the 1-core and 0-core scenarios, and emergency shelters 16, 24, 34, and 127 failed to play a rescue role and must be strengthened. The study found the local stability of the road network to be poor; multiple local road networks were not closely linked with one another, which led to a lack of close connections between most emergency shelters and other road nodes. As a result, post-disaster emergency rescue work could not be effectively completed.

4.3 Close-to-the-centre potential

The close-to-the-centre potential under the Lushan Earthquake scenario was the lowest (1/2 that of the Kangding Earthquake scenario, 1/5 that of the Wenchuan Earthquake scenario, and 1/6 of that before the earthquake). In the Wenchuan Earthquake scenario, road 32 had the maximum centre degree, and there was only one centre. In the Kangding Earthquake scenario, the close-to-the-centre potential was relatively balanced, and the value was low. The sequence of the close-to-the-centre potential was the pre-disaster scenario > the Wenchuan Earthquake scenario > the Kangding Earthquake scenario > the Lushan Earthquake scenario. The results show that the road sections at all levels of the road network structure were relatively balanced; however, the emergency refuge facilities were substandard, multiple emergency refuge areas were centred in one place, and the demand for balanced coverage was not considered. As a result, most emergency refuge facilities were essentially unable to fulfil their roles as transition stations in rescue work.

4.4 Degree centre potential

The sequence according to the network balance was the Lushan Earthquake scenario > the Wenchuan Earthquake scenario > the Kangding Earthquake scenario > the pre-disaster scenario. Thus, the ERN in the southwestern region was relatively balanced overall, with no absolute centre. The calculation results showed that after earthquakes, the road network formed multiple traffic islands, rendering the equilibrium of disaster scenarios higher than that of the road network before a disaster; the concentration of traffic islands was also higher. Therefore, earthquakes destroy the non-central nodes in road networks, resulting in a higher degree of traffic island aggregation.

5 Structure Characteristics and Planning Optimization of ERNs in Mountainous Area

5.1 Structural characteristics evaluation

5.1.1 Low overall integrity

Through the network density calculation of the current road network and an actual disaster scenario network, this study found that 16 traffic islands were formed in the Kangding Earthquake scenario, 26 were formed in the Wenchuan Earthquake scenario, and 30 were formed in the Lushan Earthquake scenario. The order of network density was the pre-disaster scenario > the Kangding Earthquake scenario > the Wenchuan Earthquake scenario > the Lushan Earthquake scenario. These results indicate that the network density could be used as an index for traffic island generation. The lower the network density is, the more easily additional traffic islands are produced. Concurrently, the road network density in this area has been impacted by disasters. The density of the road network was relatively small, indicating that the ERN density in the southwest mountainous region of China was relatively low, with no redundant road sections. Furthermore, the overall integrity of the road network was low, which could lead to the easy generation of traffic islands.

5.1.2 Poor stability and vulnerability

The ERN in China's southwest mountainous region comprises multiple local networks; however, due to the complex topography of the area, there were only a small number of high-K-core clusters, and the ratio of each K-core differed in each disaster scenario. A smaller K-core value indicates poor local stability of the road network. Once the network is disturbed, chain reactions occur, and the entire network is likely to fall into paralysis. Notably, the order of the local stability of the network structure was the pre-disaster scenario > the Kangding Earthquake scenario > the Wenchuan Earthquake scenario > the Lushan Earthquake scenario. This result was linked to the overall completeness of the road network, indicating that this aspect and local stability shared a degree of correlation.

5.1.3 Balanced overall while imbalanced locally

The overall structure of the ERN in the mountainous region of Southwest China was relatively balanced and lacked an absolute centre. However, locally, different road sections showed different degrees of importance, which reflected imbalanced characteristics. Therefore, the importance degree of different road sections must be determined. In addition, the current emergency refuge facilities are randomly located and are thus not effectively configured according to important road sections, which lead to inefficient utilization.

5.1.4 "Aggregation-breakage" distributional characteristics

To understand the spatial distribution characteristics of the emergency network in the southwest mountainous region of China, more critical road sections of the network were selected for spatial visualization analysis. For example, according to the spatial visualization analysis, road section nodes with network node degrees of 5 and 6 and those with the top 10% betweenness values can be identified as emergency roads. The network node degree is the simplest and most intuitive physical measure to describe the characteristics of nodes (Wellman et al. 2008), and it is one of the results of the degree centre potential calculation. It indicates how many nodes a certain node is connected to, thereby reflecting the connectivity and importance of the node. Road sections with a higher degree are more fragmented (Fig. 5). Both high- and low-grade arterial roads indicated scattered distribution characteristics. Notably, there were more low-grade village and town-branch road systems near points with higher degrees. However, every traffic of villagers was initially carried out through low-grade village branches, which meant that there were more village settlements nearby. Accordingly, emergency shelters can be situated along road sections with higher network degrees according to the characteristics of this law to ensure that nearby residents have accesses to effective rescue services following a disaster and to reduce losses of life and property. However, roads with a greater number of intersections had an obvious tendency of agglomeration and were primarily concentrated in the vicinity of high-grade arterial roads and their intersections, indicating clustering distribution characteristics (Fig. 6). Moreover, points with high interfacial numbers have a great impact on the entire emergency rescue system and affect the rescue efficiency of the overall emergency network. Certain pre-disaster protection measures can be taken to ensure the efficiency of regional emergency rescue work in the wake of a disaster.

5.2 Optimization strategies

ERN planning in the mountainous region of Southwest China includes disaster prevention and mitigation. Therefore, ERNs must adhere to rapid-response requirements, and limited resources must be applied to improve the rescue efficiency. The network efficiency is typically related to the network structure; thus, planning linked to the ERN in the mountainous region of Southwest China must consider the structural characteristics, analyse relevant patterns, and understand the attributes of the local network and individual road sections. Accordingly, on the basis of existing planning, optimization, which included the layout of emergency refuge facilities and increasing the prevention and control areas of key road sections, was conducted. The following steps were included (Fig. 7). (1) Emergency shelter facilities must be rearranged and optimized. According to the calculation and analysis, the existing distribution of facilities does not correspond to the road network characteristics. Therefore, the spatial layout and level configuration of emergency shelter facilities must be optimized according to the structural characteristics. (2) Prevention and control areas must be added to key road sections. Existing disaster prevention plans have primarily created disaster prevention areas based on geological hazard points. These geological hazard points principally represent the areas where disasters have previously occurred. Such planning denotes a degree of passivity; that is, it can only target areas in which disasters have previously occurred and cannot provide an effective planning solution for areas where no disasters have occurred. If road sections with a strong intermediary role in an area can be identified according to the characteristics of the particular road network and a degree of prevention and monitoring

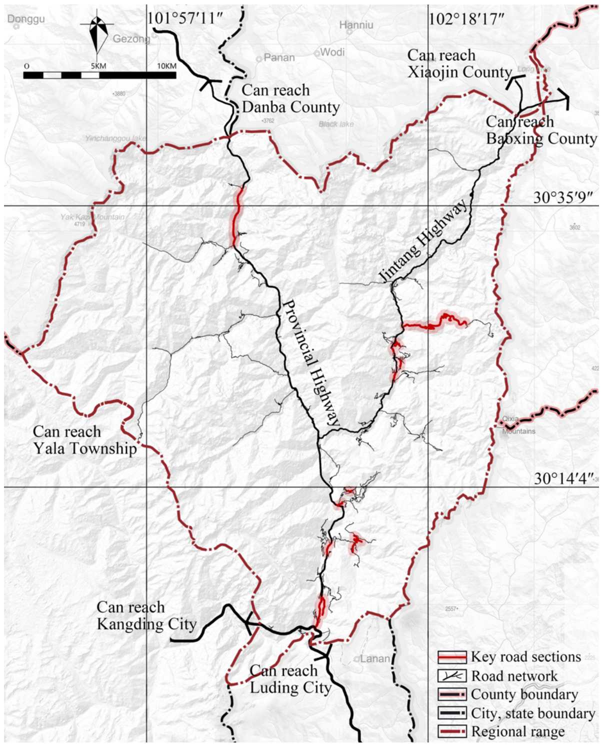

Fig. 5 Spatial distribution of the top 10 key road sections in degrees.

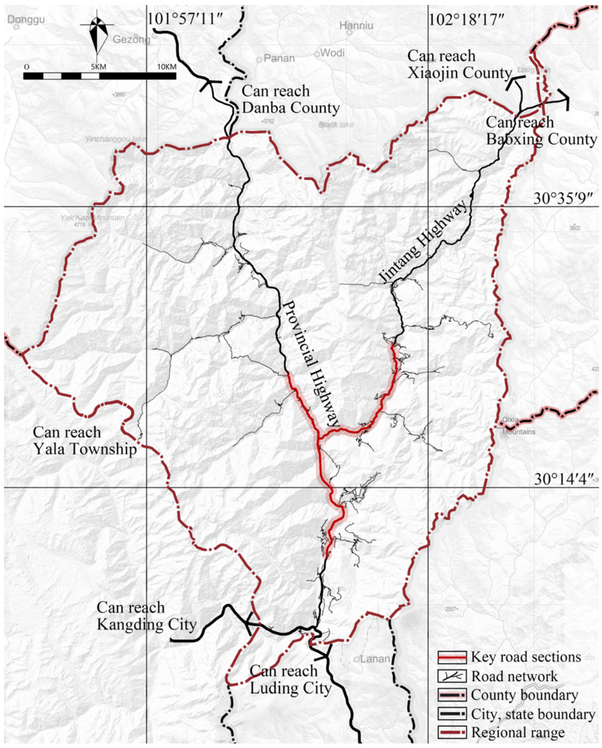

Fig. 6 Spatial distribution of the top 10 key road sections in betweenness.

can be performed, these road sections can be greatly improved. This approach can, in turn, improve the

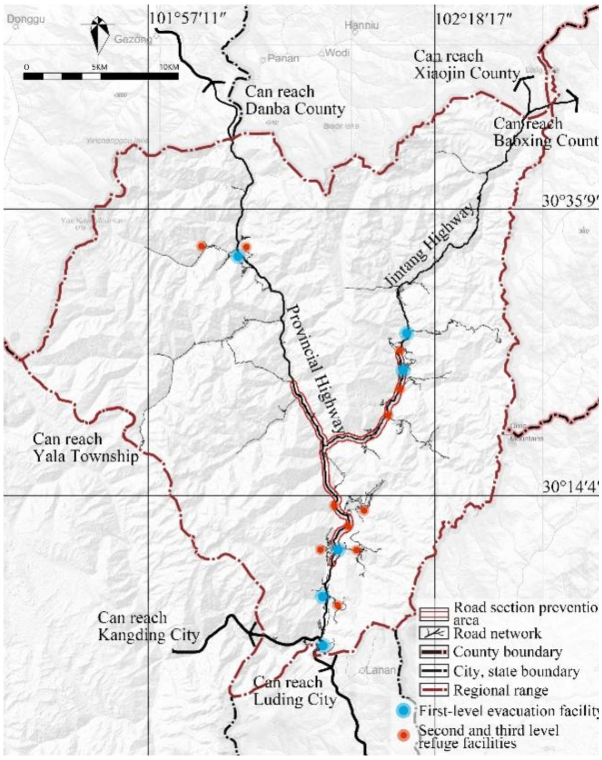

Fig. 7 Optimization of disaster prevention and mitigation planning in the study area.

resilience of a network and its ability to recover from a disaster.

6 Conclusion

Based on complex network system theory and computer simulation methods, this study introduced complex network theory into the field of urban and rural transportation planning. We discussed the topological structure and progression of mechanisms related to ERNs based on different disaster scenarios, analysed the patterns of the networks, and explored the establishment of a network analysis method for application to an emergency mountainous area road network. Given the frequent geological disasters in China and the failure of ERNs in disaster mitigation, we conducted a case study of the road system in the Kangding section of the Dadu River Basin. This area is a typical disaster-prone region in China's southwestern mountainous region and was selected to construct a road network model and test the network topology analysis. The main findings of this research are as follows. First, a set of calculation methods to measure the structural change characteristics of road networks under earthquake scenarios was established: Complex Network Analysis was used to analyse the relationships between the four characteristic indexes of mountain roads and the degree of earthquake impact under the Lushan, Wenchuan, and Kangding Earthquake scenarios. The conclusions are consistent with the real earthquake scenarios. Therefore, the model was successfully validated, confirming that it can be used by civil defence, emergency management, and other organizations to predict, and prepare for disruptions caused by future earthquakes and, by extension, albeit with reduced confidence, by other natural or human-induced incidents. Second, the structural characteristics of the highway network in mountain disaster areas were assessed. For example, the overall integrity of the network is poor, traffic islands are easily generated, the local stability of the network is poor, local networks are likely to affect each other, and cascade failures will occur after an earthquake. The structure is balanced overall but presents partially non-balanced structural characteristics. Sections with different attributes present "aggregation-breakage" spatial distribution characteristics. Finally, according to the conclusions drawn by the research, corresponding planning and optimization strategies were proposed to achieve pre-disaster prevention and real-time monitoring of the disaster scenarios of the ERN, as needed. The study results are expected to provide a scientific basis for emergency route selection, road repair, and disaster prevention and mitigation in cities and towns in mountainous and disaster-prone regions in Southwest China.

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References

Ball MO, Nemhauser GL (1979) Matroids and a reliability analysis problem. Math Operations Res 4(2): 132-143. https://doi.org/10.1287/moor.4.2.132

Bell M (2000) A game theory approach to measuring the

performance reliability of transport networks. Transp Res Part B-Methodological 34(6): 533-545.
https://doi.org/10.1016/S0191-2615(99)00042-9
Benrhaiem W, Hafid A, Sahu PK (2020) Reliable emergency message dissemination scheme for urban vehicular networks. IEEE Trans Intelligent Transp Syst 21(3): 1154-1166.
https://doi.org/10.1109/TITS.2019.2902850
Chen A, Hai Y, Hong K L, et al. (2002) Capacity reliability of a road network: an assessment methodology and numerical results. Transp Res Part B 36(3): 225-252.
https://doi.org/10.1016/S0191-2615(00)00048-5
Choi JH, Barnett GA, Chon BS (2010) Comparing world city networks: a network analysis of Internet backbone and air transport intercity linkages. Glob Networks 6(1):81-99.
https://doi.org/10.1111/j.1471-0374.2006.00134.x
Derrible S, Kennedy C (2012) The complexity and robustness of metro networks. Phys A-Stat Mech Its Appl 389(17): 3678-3691.
https://doi.org/10.1016/j.physa.2010.04.008
Huang X, Song L (2018) An emergency logistics distribution routing model for unexpected events. Ann Operations Res 269(6): 1-17.
https://doi.org/10.1007/s10479-016-2300-7
Kaviani A, Thompson RG, Rajabifard A, et al. (2018) A model for multi-class road network recovery scheduling of regional road networks. Transp 1: 1-35.
https://doi.org/10.1007/s11116-017-9852-5
Kato T, Uchida K, Lam WHK, et al. (2020) Estimation of the value of travel time and of travel time reliability for heterogeneous drivers in a road network. Transp 48: 1639-1670.
https://doi.org/10.1007/s11116-020-10107-x
Kroes E, Koster P, Peer S (2017) A practical method to estimate the benefits of improved road network reliability: an application to departing air passengers. Transp 4: 1-16.
https://doi.org/10.1007/s11116-017-9764-4
Leng JQ, Yang LH, Liu WY, et al. (2017) Measuring road network vulnerability with sensitivity analysis. PLOS ONE 12(1).
https://doi.org/10.1371/journal.pone.0170292
Liu W, Hu G, Li J (2012) Emergency resources demand prediction using case-based reasoning. Safety Sci 50(3): 530-534.
https://doi.org/10.1016/j.ssci.2011.11.007
Manfre LA, Cruz BB, Quintanilha JA (2020) Urban settlements and road network analysis on the surrounding area of the Almirante Alvaro Alberto Nuclear Complex, Angra dos Reis, Brazil. Appl Spat Anal Policy 13(1): 209-221.
https://doi.org/10.1007/s12061-019-09299-2
Menoni S (2001) Chains of damages and failures in a metropolitan environment: some observations on the Kobe earthquake in 1995. J Hazardous Mater 86(1-3):101-119.
https://doi.org/10.1016/S0304-3894(01)00257-6
Mooselu MG, Liltved H, Nikoo MR, et al. (2020) Assessing optimal water quality monitoring network in road construction using integrated information-theoretic techniques. J Hydrol 589.
https://doi.org/10.1016/j.jhydrol.2020.125366
Sarma SS, Sinha K, Sub-R-Pa C, et al. (2020) Optimal distribution of traffic in manhattan road networks for minimizing routing-time. IEEE Transactions on Intelligent Transportation Systems 99: 1-22. https://doi.org/10.1109/TITS.2020.2994836
Sheu JB (2007) An emergency logistics distribution approach for quick response to urgent relief demand in disasters. Transp Res Part E Logistics & Transp Rev 43(6): 687-709.
https://doi.org/10.1016/j.tre.2006.04.004
Soltani-Sobh A, Heaslip K, Stevanovic A, et al. (2016) Evaluation of transportation network reliability during unexpected events with multiple uncertainties. Int J Disaster Risk Reduction 17: 128-136.
https://doi.org/10.1016/j.ijdrr.2016.04.011
Von Ferber C, Berche B, Holovatch T, et al. (2012) A tale of two cities. vulnerabilities of the London and Paris transit networks. Computer Science 4(1):74-89.
https://doi.org/10.1007/s12198-012-0092-9
Wang Y, Wang J (2020) Measuring and maximizing resilience of transportation systems for emergency evacuation. IEEE Transactions on Engineering Management.
https://doi.org/10.1109/TEM.2019.2949098
Wellman B (2008) The development of social network analysis: A study in the sociology of science. Contemporary Sociology 37(3): 221. https://doi.org/10.1177/009430610803700308
Yang S, Hu F, Thompson RG, et al. (2018) Criticality ranking for components of a transportation network at risk from tropical cyclones. Int J Disaster Risk Reduction 28.
https://doi.org/10.1016/j.ijdrr.2018.02.017
Yang Y, Liu Y, Zhou M, et al. (2015) Robustness assessment of urban rail transit based on complex network theory: A case study of the Beijing Subway. Safety Sci 79: 149-162.
https://doi.org/10.1016/j.ssci.2015.06.006
Yucel E, Salman F S, Arsik I (2018) Improving post-disaster road network accessibility by strengthening links against failures. Eur J Operational Res 269(2): 406-422.
https://doi.org/10.1016/j.ejor.2018.02.015
Zhang J, Wang S, Zhang Z, et al. (2016) Characteristics on hub networks of urban rail transit networks. Phys A Stat Mech Appl 447: 502-507. https://doi.org/10.1016/j.physa.2015.12.060
Zio E, Golea LR (2012) Analyzing the topological, electrical and reliability characteristics of a power transmission system for identifying its critical elements. Reliab Eng Syst Saf 101(1): 67-74.
https://doi.org/10.1016/j.ress.2011.11.009