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Study on Seismic Resilience Assessment Method for Road Traffic Network

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Abstract

Road traffic network is an important lifeline engineering of a city, and it is one of the main dependencies for a city to maintain its functions. With the continuous development of transportation technology, much long-span complex bridges and expressways were built, and lead to the urban traffic network becomes denser and develops rapidly towards three-dimensional direction. By 2017, 398,000 kilometers of urban roads had been built, with an area of 788,526,000 square meters and 69,816 urban Bridges in China. Once such a large-scale road network is damaged by the earthquake, on the one hand, the destruction of the road network itself will bring huge economic losses; on the other hand, it will seriously hinder the earthquake emergency rescue and post-earthquake recovery and reconstruction work. Because the road traffic network undertakes the important tasks of transporting disaster relief materials, evacuating people in disaster areas, transporting rescue forces and ensuring post-disaster recovery and reconstruction after the earthquake, it has a great impact on the rapid recovery of the overall function of the city. The disruption of road traffic can turn many areas into "islands" as they lost the access to outside world. Before the rescue work is carried out, a lot of time must be spent to repair the rescue road connecting the "island", which makes it difficult to invest a lot of relief forces in time and the wounded cannot be transported to medical institutions. This process involves not only the earthquake safety of buildings, but also puts forward higher requirements for the maintenance and rapid recovery of urban functions after the earthquake. Under this background, this paper proposes an evaluation method of road traffic network recoverability based on post-earthquake disaster losses.

In this paper, the methods of seismic damage assessment of road network units are summarized firstly, and the methods of seismic damage assessment of each road network units are selected by comparing and analyzing the characteristics and applicable scope of each method. Secondly, a model for calculating road element importance coefficient is established using road connection degree, intermediary, length, and number of lanes as the main parameters, and then the road element importance coefficient is modified according to the regional location of the road element. Thirdly, considering the influence of disaster loss, the total cost, the road element importance coefficient and the structure type of road traffic network, an evaluation model of road traffic network resilience after earthquake is established. Finally, as a case study, the resilience of a small road traffic network under different intensity earthquake were studied using of the evaluation model.

Keywords: Road traffic network, Seismic resilience, Assessment method, Element importance coefficient, Damage costs.

1. Introduction

The huge energy released by the earthquake will cause damage to the living environment of human beings and cause huge social and economic losses. Due to its strong destructive power and its unpredictable characteristics, it is doomed that human beings will inevitably be hurt in the face of earthquakes. Even in today's highly developed science and technology, there is no way to achieve complete damage. Several famous international earthquakes, such as the Wenchuan earthquake, Taiwan chi-chi earthquake, Kobe earthquake, Northridge earthquake, east Japan earthquake, etc., have caused serious casualties and economic losses. In addition to these strong earthquake, some of the smaller earthquake although could not cause massive damage, but can cause very big effect to the normal operation of the urban functions and brings great inconvenience to people's production and life. With the acceleration of urbanization, a large number of people flood into cities, resulting in more and more dense urban population. People's dependence on urban functions becomes more and more obvious, and higher requirements are put forward for the maintenance and rapid recovery of urban functions after the earthquake. Under this background, the design of earthquake resilience emerges as the time required.

Road traffic network is important lifeline engineering in a city, and it is one of the main dependencies for the maintenance of a city's functions. With the continuous progress of traffic science and technology, much long-span, complex system bridges and expressways are being built continuously, and the urban traffic network is becoming more and more intensive. Once the road network of such a large scale is hit by an earthquake, on the one hand, it will bring huge economic losses because of the destruction of the road network itself, as shown in figure 1(a) to figure 1(d). On the other hand the earthquake emergency relief and post-earthquake recovery and reconstruction work will be blocked because the urban road network bears the important tasks of evacuating the people in the disaster areas and delivering rescue forces, as shown in figure 2(a) to figure 2(b). In 2008 China's Wenchuan earthquake, a large number of roads, bridges and tunnels in the disaster areas were damaged. Because of the interruption of road traffic, many areas lose the access to the outside world and forming "isolated island" which need to spend a lot of time to open up "isolated island" rescue roads before the rescue work begins. For example, in the Wenchuan county, it took three days to get through the traffic line to the county, while the connection to Beichuan was even more delayed. The formation of these isolated islands makes it difficult for disaster relief forces to quickly and massively invest, and the injured cannot be transported to medical institutions in time for treatment, which has a great impact on the efficiency of post-earthquake emergency rescue and also delays the post-disaster recovery and reconstruction.

It can be found from the analysis above that the rapid recovery ability of a regional transportation network has a very important impact on the smooth development of all kinds of rehabilitative measures and is the basic guarantee for earthquake relief and recovery and reconstruction. From the study of seismic resilience evaluation method of transportation network, we can find a scientific and reasonable method to grasp the resilience capacity of a regional transportation network more accurately. The main purpose of this paper is to establish a set of seismic toughness evaluation methods for road traffic network.

At present, the earthquake resilience in international transportation network system evaluation method research is still in its infancy, “resilience” was firstly used to psychology related study, and then Holling [1] in 1973, engaged in ecology gives the definition of recoverability - a system for temporary interference absorptive capacity and interference state after the recovery ability evaluation index. For nearly half a century, the concept of recoverability has been widely used in different research fields. Mahin, in the 16WCEE report pointed out that in the field of the engineers in the future will face two major challenges, one is the improvement and extension of the concept of performance based earthquake engineering, and the other is for solving the problems related to resilience [2]. This shows the importance of the concept of resilience in the field of seismic engineering. Wolshon, Dewar, Heaslip, Buckle, Cimellaro et al. have conducted preliminary studies on the seismic resilience of transportation network systems [3].

It can be found from the summary of relevant literature that the research on the earthquake resilience evaluation of road network system has been carried out in the world. Some evaluation methods for the traffic network system using different ideas have been proposed by many scholars. However, generally speaking, most of the current evaluation methods are still in the stage of top-level design and frame construction. Through the analysis of the author, it is believed that there are still some deficiencies in the current research, such as: the selection of evaluation indicators is not reasonable enough to accurately reflect the overall function of the road network; There is still a lack of reliable damage state evaluation method for many units in the traffic network, which makes it impossible to accurately evaluate the overall performance of the network. In view of these reasons, some of the current methods themselves are not practical enough to promote the application. The author while absorbing the existing studied results starts with the damage state performance evaluation of the basic unit of traffic network. The concept of network unit importance is introduced to reflect the contribution of different units to the overall function of the network. On this basis, the repair expenses of road network system caused by earthquake are selected as the main index, and the seismic resilience evaluation model of road network is established.

a) Collapsed bridge during Kobe earthquake

b）Damaged highway bridge in Loma Prieta

c) Cracked road in Indonesia tsunami earthquake

d）Damaged roads in Wenchuan earthquake

Fig.1 – Examples of road traffic network earthquake damage

a) Transportation routes disrupted by Kobe earthquake

b) Rescue vehicles blocked by the damage road in Ludian earthquake China

Fig. 2 – Road traffic network earthquake damage affected emergency rescue work

2. Seismic damage assessment method for traffic network elements

2.1 Seismic damage assessment method for element

When a strong earthquake occurs, the road network elements affected by the earthquake may be damaged to different degrees. Whether it is roads, bridges or tunnels, the destruction will lead to the reduction of traffic capacity. How to quantitatively evaluate the change of network traffic capacity after the unit is affected by earthquake is a problem to be solved. In this paper, the post-earthquake repair cost of road network elements are taken as the main parameter to represent the change of element traffic capacity and the seismic resilience evaluation model of road network is established based on this parameter. In general, we can consider that the loss of the element is roughly the same as the repair cost. The more the repair cost is, the more the capacity is weakened and the less recoverable it is. The repair cost of the road network element is mainly related to the damage degree of the unit itself. In addition, the destruction or collapse of buildings can lead to the formation of debris near the road, which can block the road or reduce the traffic capacity of the road. In the post-earthquake recovery phase, this debris will also need to be cleared and additional costs will be brought.

The study on the seismic damage assessment method of traffic network elements started earlier in the world. Research has been done in Japan, China, the United States and elsewhere since the 1980s and 1990s. But in the subsequent decades, thorough study of these evaluation methods are less [4], mainly because the lack of enough seismic damage data which makes it impossible to build reliable models. In addition to such methods, which rely on seismic damage statistics, there are other evaluation methods which mainly based on numerical simulation of structural damage, but their reliability has not been tested [5]. The Wenchuan earthquake in 2008 is one of the most serious disasters in the world nearly 20 years, and a large number of bridges and roads damaged in the earthquake. The author's research team collected damage data from more than 2,000 bridges and dozens of roads in the disaster area, and the data were used to build earthquake damage assessment models for bridges and roads.
Nine indexes including soil type, structure type, bridge line type, pier type, foundation type, support type, bridge scale, fortification intensity and input earthquake intensity were selected as the main factors influencing the seismic damage of bridges. Through multivariate nonlinear regression analysis, the relationship between the seismic damage index of the bridge and the 9 influencing factors is obtained, and then the evaluation model of the seismic damage of the bridge is obtained.

$$Y = c\prod_{i,j=1}^{m,n} a_{ij}^{x_{ij}} \tag{1}$$

Where c is the constant coefficient, a_{ij} represents the regression coefficient in item j of the ith seismic impact factor, and x_{ij} represents the parameter value of item j of the ith seismic impact factor of the bridge. If the bridge conforms, the value is 1; if not, the value is 0. Through regression analysis, the parameters of each influence factor were obtained, and the specific process and parameter values can be referred to the literature [6].

Selection of road grade, roadbed type, roadbed height difference, revetment material and type, site category, slope height, slope gradient, slope protection type, input intensity and fortification intensity as the seismic damage factors, road damage assessment was established by statistical regression model, as shown in Eq. (2), the regression results of parameters can refer to literature [7]

$$\overline{ind}_i = c_0\prod_{j=1}^{n}\prod_{k=1}^{r_j} c_{jk}^{\ x_{ijk}} \tag{2}$$

Where $\overline{ind}_i$ is the average seismic damage index of road i, c_0 is constant coefficient, n is the classification of seismic influence factors, r_j is the number of sub-classes of the i class factors, c_{jk} is the regression coefficient. Seismic damage assessment methods for tunnels are very few in the world. This is mainly because the seismic damage is relatively small compared with bridge and road for tunnel is an underground structure. But particularly the Kobe earthquake in 1995 and the chi-chi earthquake in 1999, the former caused more than 30 tunnels damaged, while the latter caused more than 40 tunnels damaged. The evaluation model established by X. Fang in 2008 is recommended to evaluate the seismic damage state of tunnels in this paper. In this model, intensity, overburden thickness, surrounding rock classification, whether to go through faults, length and stability of mouth openings are selected as the seismic damage factors. Based on the seismic damage data in Kobe earthquake, the relationship model between the tunnel seismic damage index and seismic damage factors is established by regression, as shown in Eq. (3), and the specific process could referred to [8].

$$y_i = \sum_{j=1}^{7}\sum_{k=1}^{r_j}\delta_{i(j,k)} b_{jk} \tag{3}$$

Where b_{jk} is the value of each influence factor obtained by statistical regression, $\delta_i(j,k)$ is the parameter value of item k in the j influence factor.

2.2 The influence of building damage on the capacity of road network units

In the urban road traffic system, the earthquake damage of buildings often has a serious impact on the traffic capacity of the road network, which has been confirmed by the experience of many large earthquakes in the world [9]. The main cause of this problem is the large concentration of urban population. On the one hand, the growing population makes the density of buildings increase and the height of the building increasing too. Obviously, more density of the buildings and more debris will produced under the same earthquake, while the increase of building height will greatly increase the impact range after the fall of building debris, which will have a greater impact on the traffic capacity of the road. On the other hand, the traffic flow burdened by urban road network is also increasing with the increase of population, and which puts higher requirements for the capacity of the road traffic network.

There are few studies on the influence of damaged building on the traffic capacity of roads in the world. Based on the seismic damage data of Tangshan earthquake, Li established a method to calculate the building debris accumulation amount [10], and then calculated the passage probability of the corresponding road using the debris accumulation amount. Y. Li et al. modified the model by investigating the characteristics of street buildings and roads in mountain cities [11]. Different scholars analyzed the collapse models of the buildings along the street and found that the distribution range of the debris pile after the collapse of various buildings generally did not exceed half of its height. For conservative, 2/3 of the height of the building is recommended. Based on the established model, a method to calculate the debris produced by the damaged buildings along the road is developed in this paper.

The rich width of the road can be calculated by Eq. (4)

$$w_R = w_d + d_{ijk} \tag{4}$$

Where w_d is the distance between the buildings along the street and the road, and d_{ijk} is the elevation or retreat distance of the ith floor of building j of class k.

The amount of debris accumulated after the collapse of class k buildings can be calculated by Eq. (5)

$$\Omega_k = \sum_{j=1}^{n_b}\sum_{i=m}^{n_f}\frac{\frac{2}{3}(H_{ijk}+h)-w_R}{\frac{2}{3}H_{ijk}}\cdot V_{ijk} \tag{5}$$

Where m is the number of floor corresponding to height $1.5w_R$-h, n_b is the total number of buildings of class k within the calculated range, n_f is the total number of floors of class k buildings, V_{ijk} is the volumeof floor i of building j in building k, H_{ijk} is the height of i floor of building j in the category k building, h is the height difference between the building foundation and the road surface.
The probability of debris generated by class k buildings can be calculated by Eq. (6):

$$P_k = 0.5Y_k\% + D_k\% \tag{6}$$

Where Y_k is the probability of serious damage of class k buildings, and D_k is the probability of collapse of class *k* buildings.
The amount of debris accumulated on the calculated roads after earthquake can be calculated by Eq. (7)

$$\Omega=\sum_{k=1}^{n} P_k \Omega_k \tag{7}$$

The passage probability of the road can be calculated according to Eq. (8):

$$\text{When } \Omega \leq \Omega_c,\ \ P_r = 1-\Omega/\Omega_c, \text{ while } \Omega > \Omega_c,\ \ P_r = 0 \tag{8}$$

Where p_r is the passage probability of the road, Ω is the amount of debris produced by the buildings, and Ω_c is the threshold of debris accumulation.

3. Analysis of network element importance

An element is a traffic route between two adjacent nodes in the road network, which can be a section of road, a bridge or a tunnel, or a combination of them. The road network is composed of many units with different properties. Different units play different roles in the road network, which mainly depends on the location and characteristics of the unit in the whole road network. The failure of key elements in the road network has an important impact on the global connectivity, reliability and performance of the road network. The loss of the use function of key elements often leads to the change of the global connectivity of the road network and the significant decline of the traffic capacity of the road network[12]. On the one hand, the grade and material of each element determine its own capacity, which affects the overall capacity of the road network.On the other hand, for the same element, according to its position in the road network, different road network capacity will be obtained due to the road network is a complex network and the traffic flow shared by the element at different locations is varies a lot. Their roles in post-earthquake emergency rescue and recovery and reconstruction are different, so their contributions to the resilience performance of the road network are bound to be different. In order to reflect this difference, an analysis model of the importance of a road network element is established in this paper, and the importance weight of each element can be obtained using the developed model.

3.1 Element importance analysis model

There are few studies on the importance of road network element in the world. Based on the research work of some scholars [13], an analysis model of the importance of road network was established in this paper. A road section element itself has three attributes: geometry, structure and function. Among them, the length of the section and the number of lanes can reflect the physical characteristics of the section; Connectivity can reflect the topological characteristics of road segments, and the connectivity of road segments reflects the importance of road segments and their nodes in the network from the perspective of connectivity. The dielectric centricity character of the road segment reflects the position and influence of the element in the road network from the perspective of transportation function. Therefore, the four key indicators include the length of road segment, the number of lanes, the connectivity and the mediating centrality were considered to establish the road element importance evaluation model in this paper.

$$M_i = \alpha z_i + \beta \omega_i + \gamma \rho_i + \eta \tau_i \tag{9}$$

Where M_i is the importance coefficient of the *i*th road network element,α β γ η are the weight coefficients of connectivity, mediating centrality, length of road segment and number of lanes respectively, H. Song has got a conclusion through research that the evaluation results will more reasonable when$\alpha = \beta = \gamma = \eta = 0.25$. Z_i is the connectivity of the ith road network element, ω_i is the connectivity of the ith road network element, ρ_i is the length of the *i*th road network element, τ_i is the width of the *i*th road network element.

3.2 Element connectivity

The connectivity of the road network element reflects the number of other elements directly connected to this element. Connectivity is a local feature of the network topology. The higher the connectivity degree of the unit, the more important the road network unit is. Referring to relevant studies [14], the calculation formula of the connectivity of the ith element in the road network is defined as follows:

$$z_i = \frac{B_i}{B_{tol}} \tag{10}$$

Where B_i is the number of roads connected to road i, and B_{tol} is the total number of elements in the network.

3.3 Element mediating centrality

The mediating centrality of the element represents the passing frequency of this element for the shortest path between any two different nodes in the road network. The mediating centrality reflects the importance of this road section for path selection in network and has an important influence on the overall traffic function of the road network. The higher the mediating centrality value, the more influential and important the element is. The mediating centrality value of element i can be calculated as follows:

$$b_i = \sum_{a \in v} \sum_{a \neq b \in V} \Delta(a, b|i) \tag{11}$$

$$\omega_i = \frac{b_i - minb_i}{maxb_i - minb_i} \tag{12}$$

Where $\Delta(\boldsymbol{a}, \boldsymbol{b}|\boldsymbol{i})$ is the number of shortest paths starting and ending with a, b through element i, b_i is the frequency at which the shortest path starting and ending at any two different nodes in the road network passes through element i, and V is the gather of nodes in the road network.

3.4 Element length and width

The length and width of the unit can also reflect its importance to a certain extent. As an element in the network, the traffic flow carried by this element increase with the increasing of the number of lanes and the longer of the length. Therefore, it is considered that the element with large length and width has a great influence on the network traffic capacity, and its importance is also greater. The length and width can be calculated by Eq. (13) to Eq. (14).

$$\rho_i = \frac{l_i - minl_i}{maxl_i - minl_i} \tag{13}$$

$$\tau_i = \frac{n_i - minn_i}{maxn_i - minn_i} \tag{14}$$

Where l_i is the length of element i, $\boldsymbol{maxl_i}$ and $\boldsymbol{minl_i}$ are the maximum and minimum lengths of the elements in the road network respectively. n_i is the number of lanes in element i, $\boldsymbol{maxn_i}$ and $\boldsymbol{minn_i}$ are the maximum and minimum values of the number of lanes contained in all elements of the road network, respectively.

4. Evaluation method of road network seismic resilience

4.1 Evaluation method of post-earthquake repair cost of road network element

4.1.1 Element direct repair cost

Generally, the repair cost is roughly the same as the loss cost. The direct economic loss of the element can be regarded as the repair cost of the element itself. Loss estimation is a key step to evaluate the resilience ability. The economic loss of each element at different damage levels is helpful to evaluate the resilience of each element. Through the earthquake damage assessment method of road network element introduced above, the damage level of road network element under certain earthquake intensity can be calculated, and the corresponding loss ratio can be obtained by comparing the damage level. For the seismic damage index can represent the seismic damage state [5], the product of the seismic damage index and the length (or area) of the element in good condition can be regarded as the lost length (or area) of the element by the earthquake.

When the unit cost of road network element is known, the direct repair cost of the damaged element can be calculated by Eq. (15):

$$L_z = l \times A \times S_i \times c \tag{15}$$

Where l is the total length of the element, A is the seismic damage index of the element, S_i is the median loss ratio for the corresponding failure state (refer to Tab. 1), and c is the cost per unit length of the element.

Table 1 – Seismic damage level and corresponding loss ratio of traffic network element (%)

Damage state	good	slight	moderate	severely	collapse
Loss ratio	0~10	11~20	21~40	41~70	71~100
meida	5	16	31	56	86

4.1.2 Indirect repair cost

Indirect repair costs are mainly caused by the removal of debris from buildings. The building debris will lead to the obstruction of the surrounding roads, which will hinder the recovery of the road network traffic function after the earthquake, so it is necessary to carry out the clear work as soon as possible after the earthquake. According to the road debris quantity estimation formula established above, the amount of debris to be cleared can be obtained, and then the cost required can be simply estimated:

$$L_w = \frac{\Omega}{100} \times c \quad (16)$$

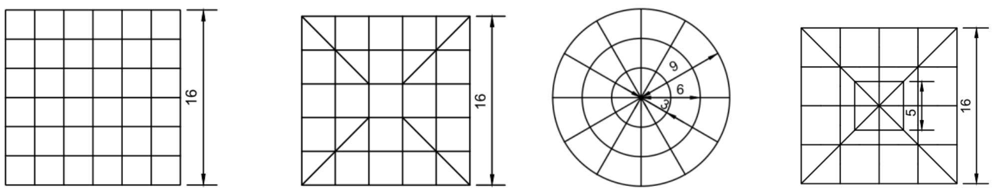
Where c is the cost standard for clearing debris from road surface.

4.2 Road network type correction

Influenced by regional economy, culture, geography and other factors, the road networks in different regions have different forms. Generally, road network types can be divided into: grid, circular radial, freestyle and hybrid, as shown in Fig. 3. The traffic characteristics are varied for different road network types. Even if the seismic loss is equal, the recovery capacity of road network may be different after the earthquake. Therefore, it is necessary to revise the road network resilience index after the earthquake based on the difference of road network types. Generally speaking, the higher the rate of network formation, the more conducive to post-earthquake rescue and reconstruction forces into the affected areas, and thus more conducive to the rapid recovery of the function of the network and the whole disaster area. In this paper, the connection degree of the road network is adopted to reflect the network formation rate of the road network. Road network connection degree is expressed in the following formula:

$$J = \frac{\sum_{i=1}^{N} m_i}{N} \quad (17)$$

Where J is the road network connection degree, N is the total number of nodes in the road network, and m_i is the number of elements adjacent to i node.



a) grid　b) Grid radial　c) circular radial　d) hybrid

Fig. 3 – Simplified diagram of four road network types

4.3 road network seismic resilience evaluation model

The road network is made up of many elements. The contribution of different elements to the function of the road network is varies, especially in the post-earthquake road network recovery process, the influence of each element on the resilience of the whole network is different, and which depends on the resilience and importance of the element itself. In this paper, element importance degree is adopted to characterize the difference of the roles of each element in the functional recovery process of the road network, and a calculation model is established for the seismic resilience index of the road network , as shown in Eq. (18) and Eq. (19).

$$R = \alpha \frac{\sum_{k=1}^{N} \beta_k R_k}{\sum_{k=1}^{N} \beta_k} \quad (18)$$

$$R_k = 1 - \frac{L_k}{C_k} \quad (19)$$

Where R is the road network post-earthquake resilience index, R_k is the post-earthquake resilience index of element *i*, β_k is the element importance degree, α is the road network type correction factor, L_k is the repair cost of element *k*, C_k is the total cost of element *k*, N is the total number of elements in the road network.

5. Case study

Part of a city's road network is selected as an example, as shown in Fig. 4. The road network contains 58 nodes and 97 road network elements, including 19 trunk roads, 10 secondary trunk roads, 6 Bridges and 3 tunnels. Based on the road network topology, Dijkstra algorithm was used to calculate the mediating centrality value of all elements in the road network topology, and the model established above was used to calculate the importance of all elements in the road network. The damage of buildings on both sides of the road is calculated by referring to the analysis results of the vulnerability of corresponding buildings. The damage state of the elements and the resilience index of the network under different earthquake intensity are shown in Table 2 and Fig.5.

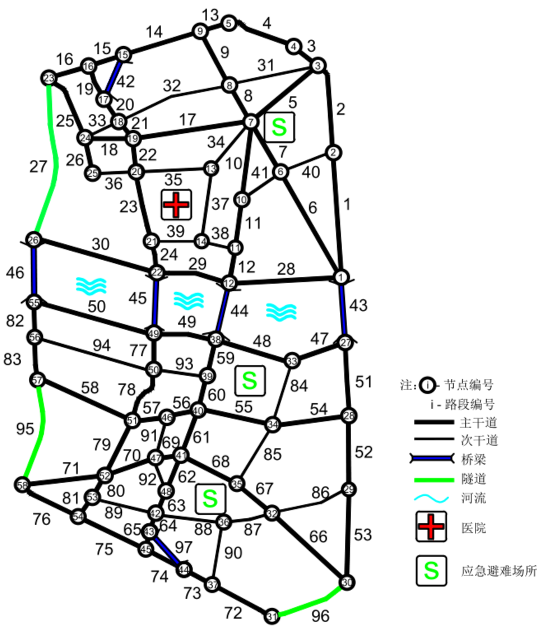


Fig. 4 – Part of the road network of a city

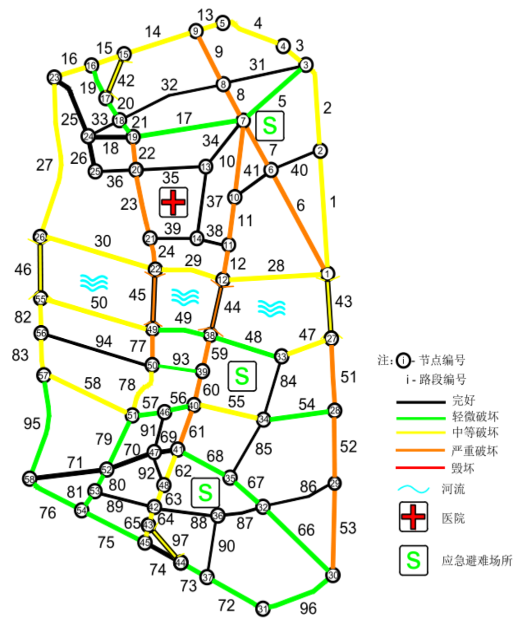


Fig. 5 – Damage state of the road network under intensity Ⅸ

Table 2 – damage and resilience of the studied road network

intensity	Damage state	Resilience index
Ⅵ	good	1
Ⅶ	19.6% slight damage	0.986

Ⅷ	27.8% slight damage 19.6 moderate damage few roads blocked by the debris	0.934
Ⅸ	23.7% slight damage 27.8% moderate damage 17.5% severe damage Debris accumulation on the road surface increased	0.794
Ⅹ	8% slight damage 24% moderate damage 39% severe damage 8% failure A lot of debris accumulated on the road surface	0.596

It can be found that when earthquake intensity smaller than Ⅷ, all the road network element has been kept in good condition. When intensity more than Ⅷ, varying degrees of damage began to happened on the road network element gradually, especially when the intensity reaches Ⅸ and above, a lot of road network cell damage occurred, and the resilience ability of the whole network also became worse gradually with the increase of intensity increase.

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