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Identification of critical links under earthquake hazards for highway networks

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Abstract: Critical links are defined as easily damaged links with massive transport in highway networks, which also need intensive improvement. The total travel time increment caused by a link's failure reflects its importance and is taken as the measure of importance. Links are subdivided into segments according to their structure features and environments. Each segment's unreliability is the probability of its function failure that cannot be recovered within an expected time. The measure of criticality is defined as the expected total travel time increment and can be obtained from the product of importance and reliability. It reflects a links' importance and ability to provide continuous service for evacuation and rescues under earthquake situation. Critical links can then be identified from the sequence of their criticality. These measures are calculated in the highway network of earthquake-hit areas in Wenchuan. Results collected in geographic information system (GIS) visualization are consistent with the situation revealed in this earthquake, which indicates that the presented method can be used to identify critical links in advance and give guidance regarding refugee evacuation and facility protection from earthquakes.

Key words: highway network; Wenchuan earthquake; criticality; importance; reliability

The latest deadly earthquake on May 12th in Sichuan province of China caused about seventy thousand deaths and over three hundred thousand injuries, which attracted global attention. The transportation system was the "lifeline" system after the earthquake happened[1]. A robust transportation network is the precondition to emergency evacuation and transportation of relief materials such as food, water, medicine and so on. How to assess the reliability of a transportation network and how to identify the critical links in advance are necessary for earthquake-prone areas, especially those located on seismic belts.

Researches on infrastructure protection mainly focus on probabilities which can be categorized into three types: connectivity reliability (also referred to as terminal reliability)[2], travel time reliability[3] and capacity reliability[4-5]. Vulnerability, exposure and criticality in various infrastructures are issues that have been most explicitly researched in recent years. Vulnerability in the road transportation system is studied not only from a safety point of view but also as a problem of an insufficient service according to Ref. [6]. Jenelius et al.[7] further pointed out that the concept of vulnerability could be divided into two parts, one containing the probability of a hazardous event and the other, which was called exposure, containing the consequences of the event in any given place. The consequences of a failing link or a group of links is called the importance of that link or group of links. If the probability of an incident is high, the components (link, etc.) are weak; and if the consequences are great, the components are important. If it is both weak and important, the components are critical.

This paper follows the above concepts to assess the links of transportation networks from different aspects. Besides the traditional reliability index, an importance index and a criticality index are introduced to measure the importance and criticality, respectively. In the following sections, we first attempt to describe the unique transportation pattern of highway networks under earthquake hazards, and then describe the procedures to calculate these indices in detail. A case study of the transportation system in earthquake-hit areas of Wenchuan is given to illustrate the practice of the methods presented in this context. The results are compared with the real situation revealed in this magnitude-8.0 earthquake to verify the methods.

1 Measures of Links

1.1 Unique transportation pattern

Seismic strong shocks will generally cause heavy damage to ground transportation systems, including highway systems and railway systems. Refugee evacuation and rescue together with the generally badly damaged transportation system makes the transportation pattern under are earthquake scenario much more different from that of ordinary scenarios. It is necessary to study how to efficiently organize people to evacuate from disaster areas and deliver relief personnel and materials to places requiring emergency treatment after a terrible earthquake. The bridges become the weakest components in the road network. The roadways may be also vulnerable especially in mountain areas, because landslides caused by aftershocks usually block the way.

Traffic mainly assembles in two directions: from and to disaster areas. On the one hand, the wounded in earthquake-hit areas need to be transferred to hospitals located in relatively safe cities. On the other hand, relief personnel including firemen, police, soldiers and medics need to get to these earthquake-hit areas to search and rescue those survivors trapped under the debris. Relief materials such as food, water, medicine and tents also need to be delivered to disaster areas.

1.2 Measure of importance

Under seismic circumstances, the wounded need to be sent

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to rescue hospitals as soon as possible. The number of people that need to be transferred depends on the distress severity the place incurs; however, we never know beforehand the real severity of a certain earthquake-hit site, or even where these sites are located. So it is hypothesized that all the local residents need evacuation which must be undertaken by the highway network. The roadways that serve more people will be considered to be more important, which is reasonable for all general situations. Relief personnel and things such as goods, medicine, food and tents are also necessary to be transferred to the disaster areas in time, which also induces part of the transportation demand. However, these demands are highly relevant to the population, because the requirements for those things are calculated according to population with a determinate amount per capita. Thus traffic demand here will be directly calculated from the population size. The consequence of a roadway's functional failure should be measured through before-after comparisons of events. If one path is blocked due to a failing component or a group of components, users use this path before having to switch to other paths, which usually results in an increase in travel time. The more the travel time increases, the more important the failing component or the group of components are. For the reasons addressed above, we construct an index named person time to evaluate the importance of roadway components just similar to the index of vehicle miles.

Cities or towns suffering from a hypothetical seism become the origins of trips under the seismic scenario. Trip destinations will be those cities or temporary encampments that can provide massive emergency treatment for the large amount of injured people and enough accommodations for more homeless sufferers. The destinations fall into these rescue places that are comparatively safe and convenient to receive outside aid. Their sites usually can be easily pre-identified due to their abundance in food storage and convenient traffic to non-hit areas. All other cities or towns are trip origins except for those few destination cities in our research areas. The origin nodes are called demand nodes and the destination nodes are called service nodes in this context. The process of calculating the importance of a link can be divided into three sequential steps: 1) Calculate the person time of an initially undamaged network; 2) Calculate the person time of the damaged network with the hypothesized failure of the link; 3) Subtract the former from the latter. Let K represent the set of links, R the set of demand nodes and D the set of service nodes. We denote the travel time from demand node i (with a population of p_i, $i \in R$) to service node j ($j \in D$) when the link k ($k \in K$) fails by c_{ij}^k, and c_{ij}^0 represents the travel time in an initially undamaged network. The formula of person time when link k fails can be expressed as

$$T_k = \sum_{i,j} p_i c_{ij}^k \tag{1}$$

Thus, the importance of link k is computed as

$$M_k = \sum_{i,j} p_i (c_{ij}^k - c_{ij}^0) \tag{2}$$

It can also be calculated as

$$M_k = \sum_{m \in K} p_m^k t_m^k - \sum_{m \in K} p_m^0 t_m^0 \tag{3}$$

where p_m^0 and p_m^k represent the number of users on link m before and after link k fails, respectively; t_m^0 and t_m^k are their corresponding link travel times. It is easy to prove that these two formulae are essentially the same.

1.3 Measure of reliability

Transportation infrastructure systems, which are degradable as a result of natural or man-made disasters, consist of many connected components such as links and bridges[1]. Usually, we treat each link or bridge as a component in estimating the reliability of a transportation network, especially in urban street networks. Each component relates to a functional failure probability, which may be estimated from other models. The transportation network is represented by a system composed of series-parallel components, whose reliability can be calculated using the "path-and-cut" method[6].

Treating a link as components is not suitable for long-distance highways. In this paper, another principle is used to subdivide the link into road segments while calculating its reliability. The principle can be described as follows: One component should have uniform road features including geological conformation, structure type and other distinguishing features that make contributions to reliability. A component defined above may be labeled with a start measure and an end measure such as mileage. Under seismic situations, the damage to highway networks mainly occur in two forms: damage to bridges and blockages of roadways by landslides. The bridges will be treated as independent components for their obvious different features from road segments. The landslides is related to many factors such as the plasticity index of clay, water condition, slop angle, slop complexity and land use[8]. So road segments with a similar geological structure on both sides are treated as a single component. A hypothesized network shown in Fig. 1 with road segments susceptible to damage can be represented by a series-parallel system illustrated in Fig. 2.

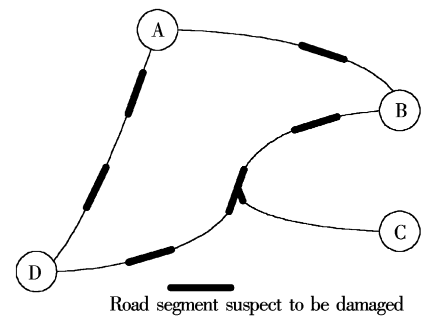

Fig. 1 Illustration of subdivision of road segments

Urgent repair is needed when damage occurs. The recovery period is generally longer when the component is seriously damaged and the losses increase exponentially as the recovery period lengthens[9]. Small damage that needs a shorter recovery period will be ignored for its minor effects. So the failure probability P_f of a component f can be presented as

$$P_f = P(F_{\text{dam}} \cap F_{\text{cov}}) \tag{4}$$

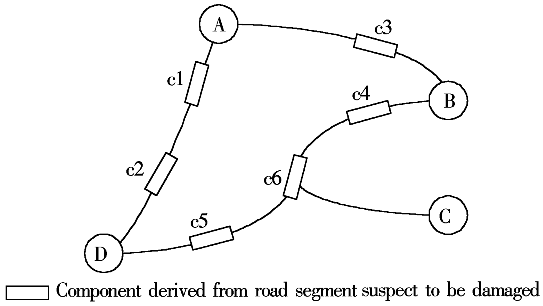

Fig. 2 Illustration of transformation from road segments to system components

where F_{dam} is the event that the component suffers from damage due to the earthquake and F_{cov} is the event that the recovery period of this component exceeds the expected recovery period. Supposing that these two events are independent, we have

$$P_f = P(F_{\text{dam}})P(F_{\text{cov}}) \tag{5}$$

Now, the remaining problems fall into how to estimate the values of damage probability $P(F_{\text{dam}})$ and recovery probability $P(F_{\text{cov}})$. Once the bridge is broken down, it is difficult to recover immediately, so the probability of event $P(F_{\text{cov}})$ is always equal to 1.0. For landslide risks in clay slopes, there are also ways of establishing their vulnerability curves[8, 10-11]. Furthermore, the geologic distribution of the vulnerability to landslides can be mapped on a map, which can help us to identify the components of links. Damage probabilities thus can be derived from their vulnerability curves.

Following the division principle above, the link is divided into many segments, with each segment treated as a component. Two probabilities (damage probability and recovery failure probability) are used to describe the components. The failure probability of link k thus can be expressed as

$$P_k = 1 - \prod_{f \in K}(1 - P_f) \tag{6}$$

The reliability of link k can be calculated by $1 - p_k$.

1.4 Measure of criticality

Critical components fall into important but weak ones. The importance measure index M which is defined in Eq. (2) reflects the link's contribution to the whole network. It will result in an increase in person time if a certain link fails as a result of some components' functional failure. The expectation of the person time increment, which reflects importance aspects and reliability aspects, can be used to identify the criticality of links. Let H_k represent the criticality of link k, and it can be calculated as

$$H_k = M_k P_k \tag{7}$$

In the extreme situation that all links have uniform importance, the criticality is just equal to the failure probability and in the situation that all links have the same reliability of 1, the criticality is just equal to the importance. Under the constraints of limited resources, such as budget, only these links with greater criticality will be reinforced.

2 Case Study

2.1 Description of study area

The Wenchuan earthquake struck China's southwest Sichuan province and neighboring areas. Our study area covers all the seriously damaged earthquake-hit areas, including 34 counties shown in Fig. 3.

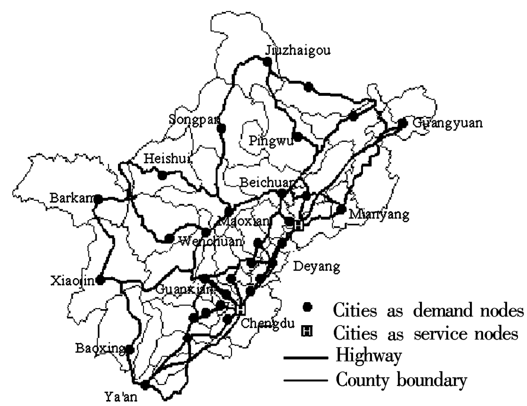

Fig. 3 Highway networks of study areas

Most of the area is mountainous with an altitude of over 1 500 m except the eastern part which belongs to Sichuan basin and a total of over 172 million people are located in this area. A railroad stretched along the eastern boundary, but it lost its function at the moment the earthquake happened, since some parts of the rail were badly twisted and some tunnels had caved in. Chengdu, the capital of Sichuan, and the Mianyang city became rescue centers because of their convenient communications to the outside and their relatively slighter damage caused by the earthquake. Both cities have aerodromes for civil and military use, which can bring rescue personnel and rescue materials from other places quickly.

The highway network in this area is composed of national highways, expressways and provincial roads. The Guangmian expressway and Chengya expressway connect cities along the eastern boundary, including Guangyuan, Mianyang, Deyang, Chengdu and Ya'an, which compose the belt of economic prosperity and a dense population. The national highway G108 also follows this direction. Other expressways are short and mainly used to connect Chengdu and the neighboring cities such as Guanxian. So nearly all expressways are located in the eastern part of the area which represents 80% of the population of the total area. In a contrast to the eastern part which belongs to the Chengdu plain, most of the middle and western parts are mountain areas whose highway network consists of provincial roads and national highways including G317, G213, G212, S210, S205, S105, S106, etc. These roads wander through the valleys along rivers or mountain bottoms.

2.2 Calculation of importance

The highway network and each county's government center are described in GIS as shown in Fig. 3. To simplify the model, we suppose that each county represents a traffic zone and all of its traffic demand congregates in its capital city depicted on the map. The population data are collected from local government websites. Traffic demand of each traffic zone is not forecasted from economic or land use features here. Instead, we use the population of each zone as its traffic demand, which corresponds to the worst scenario under which all cities suffer extreme damage simultaneously and all their inhabitants need transfer. The nodes of Chengdu and Mianyang become the service nodes and other nodes become demand nodes in the network. The demand nodes where people seek routes to the nearest service nodes only have traffic generation and the service nodes only have traffic attraction from other demand nodes. The word "nearest" here means the shortest distance. To obtain the OD(origin-destination) pattern, the minimum travel time to both service nodes is calculated and compared for each demand node in free-flow traffic state. The traffic demand is distributed to the service node with less travel time except in the situation where one minimum travel time is close to the other, when traffic demand will be distributed to two service nodes on average. This is different from the ordinary OD pattern which is usually obtained from the gravity model in the four-step forecasting procedure of travel. A transformation from population to standard passenger car is made to obtain the traffic volume on roads on the assumption that 20 people correspond to a standard passenger vehicle and all transportation tasks be fulfilled within 10 h. We use the Caliper Corporation's software TransCAD to implement the user equilibrium traffic assignment.

One link is abandoned from an original network each time to generate a scenario of the functional failure of that link. Link flow and travel time in both directions can be derived from the assignment results. Each link's importance is calculated using Eq. (3) and represented by the denary logarithm in Fig. 4. As shown in the figure, the the greatest important links belong to those expressways that are located in the eastern part. That is because the greatest amount of people reside in the eastern part and depend on those expressways, and the failure of those expressways will exert an influence on a great number of users.

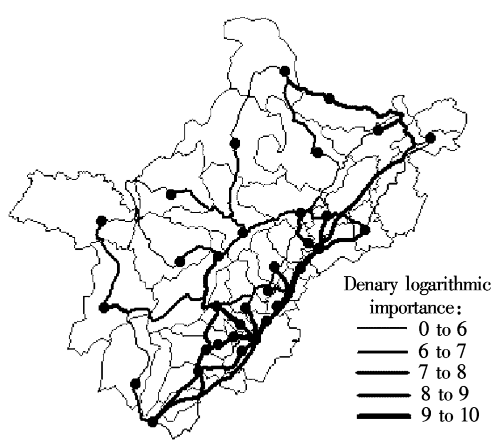

Fig. 4 Importance of highway network normalized by denary logarithm

2. 3 Calculation of reliability

Each road segment with similar roadside landscape feature is treated as a component, and so is each bridge. The recovery probability of a road segment is determined by rating slope gradients into 11 ranks with rank 0 corresponding to recovery probability of 0 and rank 10 to 1. 0. The reliabilities of all road segments have been estimated and depictured on a map as shown in Fig. 5. We can see that the relatively reliable links are also located in the eastern part including expressways and other highways. This is because the eastern part is a plain but the middle and western parts are generally mountainous areas with steep slopes beside highways. Exposure to landslides and other geological damage is much more serious in the middle and western parts.

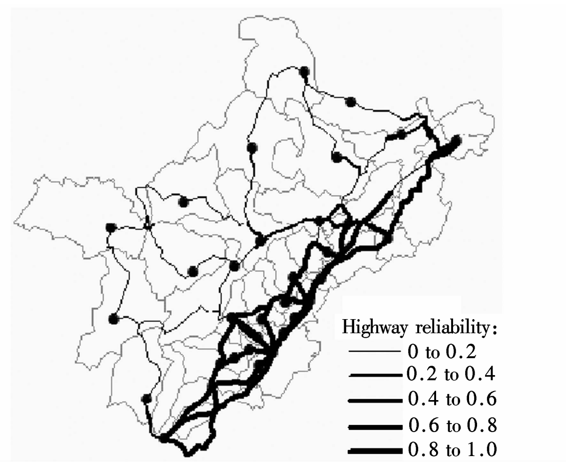

Fig. 5 Reliability of links

2. 4 Criticality of links

The criticality of links is calculated by Eq. (7) and shown in Fig. 6. We can easily identify the critical links from Fig. 6. The real critical links revealed in the Wenchuan earthquake include the segment from Guanxian to Wenchuan then to Maoxian of G213, the segment from Lixian to Wenchuan of G317 and the segment from Beichuan to Maoxian of S302. All these critical links have been identified using the method presented in this paper. For example, the identified critical segment of G213 from Guanxian to Wenchuan is the lifeline to Wenchuan and also the latest roadway that recovered from damage by four days efforts of many engineers and workers. Unlike the important and reliable links mainly located in the eastern part, these critical links may appear both in the eastern and western parts. The facts that some

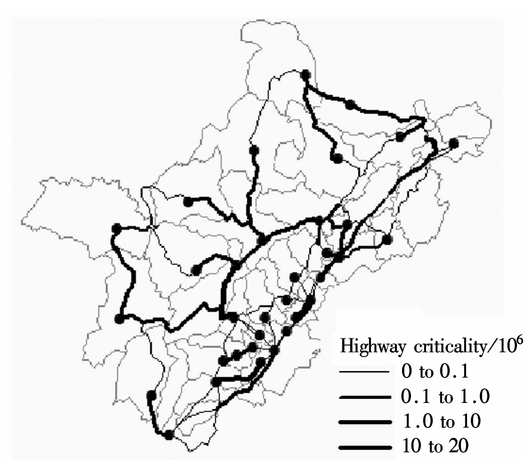

Fig. 6 Criticality of links

identified links are not revealed in this earthquake may be due to the worst scenario hypothesis that all cities suffer extreme damage simultaneously which is a little different from the real situation. These critical links need special attention, and many measures such as building retaining walls and reinforcing the structures should be applied to these critical road segments prior to others.

3 Conclusion

We have defined the concept of person time and used its increment to measure the importance of links. Link failures will result in increases of person time, so the expectation of an increment in person time when one link functionally fails reflects both importance and reliability aspects and thus is taken as the measure of the criticality of links. This measuring method is applied to the highway network of the Wenchuan earthquake-hit areas in Sichuan province of China under the worst hypothesized seismic scenario with all cities suffering extreme damage and all residents requiring transfer simultaneously. We have found that these real critical links revealed in this earthquake can all be identified with our method, which implies that this method can be used to identify critical links before a real earthquake happens.

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地震条件下公路网关键路段识别

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摘要：定义关键路段为路网中运输量大但易遭破坏的路段，也是需要重点改善的路段. 以单个路段破坏导致路网总出行时间的增加量为路段重要度指标，反映该路段对网络的贡献. 将路段按照结构特征和环境条件分段，以路段遭受破坏且不能在规定时间内修复的概率为路段不可靠度. 定义路段关键度为总出行时间增加量的期望值（路段重要度与可靠度乘积），其综合反映了路段在人员紧急疏散和救援条件下的重要程度和提供持续服务的可靠性. 通过所有路段的关键度排序识别公路网中的关键路段. 以汶川地震区公路网为例，计算各路段重要度、可靠度和关键度指标，以 GIS 地图描述其分布. 算例结果与实际情况相符，表明关键路段识别方法有效，有助于地震后人员疏散和救灾方案规划.

关键词：公路网；汶川地震；关键度；重要度；可靠度

中图分类号：U491