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RESEARCH PAPER

Vulnerability Analysis of Road Networks

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Abstract: Vulnerability of road networks measures the total loss of the network caused by sudden attack with consideration of the interactions among the units and the conscious external influences. When evaluating the vulnerability of the road network, reciprocity among units and the recovery ability of the network should be considered. The paper presents a method for vulnerability evaluation on the basis of the conception and the analysis model of the road network vulnerability. It examines the network vulnerability through final travel time loss of road user and takes sufficient consideration of the structure of the network, traffic flow state and the setting of the rescue center. A simple case study is conducted to illustrate the approach and some suggestions are proposed in terms of adding or rebuilding roads and re-locating the rescue sites.

Key Words: urban traffic; vulnerability of road network; analysis model; evaluation model; emergency rescuer

1 Introduction

Issues regarding road network vulnerability have attracted lots of attention recently. Analysis of road network vulnerability is very important in road network planning, construction and management. The important problems are "How to describe road network vulnerability?" and "How to model and assess the consequences of a disrupting event in a network?" Recently, a number of papers have presented methods that can be classified mainly into the following two types: one concerns just the change of the road connectivity based on the topology, such as Refs. [1] and [2], and the other analyzes the increased travel time related to the running of the traffic flow as well as the topological properties of the road network, such as Refs. [3] and [4].

In the paper, it is proposed that the recovery ability of the network which has a close relationship with the location and level of the rescue centers should also be considered in addition to the topological properties and traffic flow in analyzing road network vulnerability .After proposing the concept and analysis model for road network vulnerability, an assessment method is described in the following sections.

2 Concept of road network vulnerability

Nowadays, the concept of road network vulnerability is not uniform. It was Berdica who first proposed the concept. According to him, road network vulnerability is a sensitivity coefficient that is easily affected by accidents and finally makes the service level decline sharply. The service level of a road network describes the probability of the road being connected or used at a certain time[5]. According to Tuyinfei from Tongji University, the network's inability to withstand abnormal events is one of the vital causes of significant losses, and this is one of the properties of a road network that can constitute road network vulnerability[2]. Husdal's view is that road network vulnerability describes the non-functioning of a network under certain conditions. According to the former researches, the concept of road network vulnerability is to emphasize the loss or effect after the network has been attacked by an accident[6].

In the paper, road network vulnerability can be described as follows: when some units of the road network (including nodes and road links) are attacked, the loss will spread to other units under both the units' own reciprocities and continuing impact of outer factors. Road network vulnerability means the final loss of the whole road network.

Road network vulnerability can be regarded as a result of comprehensive actions of immunity abilities, running state of traffic flow as well as recovery abilities of the network. The purpose of road network vulnerability assessment is to find the

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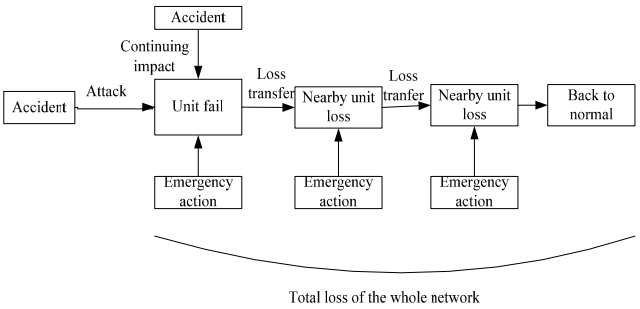

Fig. 1 Formation mechanism of road networks vulnerability

weak link, in other words, to find the key point of the whole network where the loss is the most significant when the same level of attack is suffered. Therefore, road network vulnerability can be measured by the most significant loss of the whole network caused by the failure of the corresponding road network unit.

3 Analysis of road network vulnerability

The worsening of road network vulnerability comes from the combined function of road conditions, network structure, traffic flow state, rescue center setting, resource scheduling, recovery strategies and so on. The formation mechanism of road network vulnerability is shown in Fig. 1.

When a unit of a network has been attacked and has failed because of an accident, traffic officials take measures immediately. At the same time, loss is transferred among other units under the effect of the continuing impact of the accident, changing traffic flow, the rescuing process, road connectivity and some other factors. Vulnerability has been irritated followed by the loss transferring. The whole process lasts until the function of the road network comes back to normal. The road network vulnerability measures the total loss to the whole network in the process. Loss mentioned here could be the decline of road connectivity, traffic efficiency and so on, it is the sum total of the loss of all the units.

Let X_i denote the network loss when unit i has been attacked; let I be the number of network units; let K be the number of the failure units under the situation; let k denote the kth failure unit and x_k denote the loss of the unit k. Thus,

$$X_i = \sum_{k=1}^{K} x_k (k = 1,2,3\cdots, K, i = 1,2,3\cdots, I) \tag{1}$$

Because x_k has relationships with the rescue technology of unit k and loss of upstream unit, assume that the unit loss transfers one by one, so let k–1 denote the nearest upstream unit and R_x denote the rescue technology of unit k. Thus,

$$x_k = f(x_{k-1}, R_k) \tag{2}$$

Finally, the vulnerability of the road network denoted by V could be measured by the most significant loss of the whole network caused by the failure of the corresponding road network unit.

$$V = \max X_i (i = 1,2,3,\cdots, I) \tag{3}$$

4 Assessment of road network vulnerability

As a measure of reduced performance of the network, the road network vulnerability seems to be complex. In the paper, several factors have been considered in its assessment including network topology, state of the traffic flow and the location and capacity of the rescue center. The paper uses the final users' lost travel time of the whole network as a measurement. Because the nod damage can be regarded as the damage of the links connected with the nod, the paper just takes the situation of links being damaged for example.

By closing the links located on the shortest route and then calculating the users' lost travel time one by one, the paper has built the road network vulnerability assessment model as follows.

Assume that all users intend to travel along the shortest route. Once the road link has been damaged, there appears to be no new traffic demand for the reason that the information has been spread immediately.

When link k of the network is closed, the users will have two choices .The first is to wait for the link to be repaired and to reopen again and then they will travel along the original shortest route denoted by r_{original}. The second is to travel in the reverse direction by evacuation to find the nearest export and travel along the route that is now the shortest, denoted by $r_{\text{substitute}}$ as substitute.

Suppose now that link k is located along the route r_{original}. At t=0, this link is unexpectedly closed for all traffic .Traffic officials mobilize the professional rescue team from the near rescue center to take action immediately. The rescue time has a close relationship with the level of rescue and the distance between the rescue center and the accident point. Thus, the function of the rescue time could be

$$I_r^{\,k} = a_R \frac{D_{R-k}}{v_r} \tag{4}$$

where $I_r^{\,k}$ denotes the rescue time, which is also the longest waiting time to the users, D_{R-k} denotes the length of the shortest route between the rescue center and the link k, v_r denotes the travel speed of the rescue team and a_R is the parameter related to rescue level or capacity.

Situation 1: If the users think that the lost time when traveling along $r_{\text{substitute}}$ is longer than the waiting time, they will choose to wait until the link reopen again.

In this case, the users' lost time can be calculated as

$$I_w^{\,k} = I_r^{\,k} = a_R \frac{D_{R-k}}{v_r}, \text{when } I_r^{\,k} \le \Delta I_{k,m} \tag{5}$$

where $I_w^{\,k}$ denotes the waiting time for the users when link k is closed, $I_r^{\,k}$ denotes the rescue time of link k, and $\Delta I_{k,m}$ denotes the users' lost time when choosing to travel along $r_{\text{substitute}}$.

Situation 2: if the users think that the lost time when