EARTHQUAKE PERFORMANCE OF HIGHWAY SYSTEM IN TOKYO

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SUMMARY

The purposes of this study were to develop a methodology for estimating the performance of highway network systems subjected to earthquakes and to develop procedures for characterizing the post-earthquake role of each road in the system. A Monte Carlo technique taking into account seismicity, ground conditions, and the strength of the structures in the system was used to simulate the physical damage to the highway system. A detailed method using flow analysis and taking into account the effects of the decreased capacity of the road after the earthquake was then used for examining the functional damage and the role of each road in the highway system. Lastly, these methods were used to evaluate the earthquake performance of the highway systems in Tokyo, Japan.

INTRODUCTION

Earthquakes have resulted in highway system malfunctions that not only obstructed the action of emergency vehicles such as fire engines and ambulances immediately after the earthquake but that also interfered with domestic and industrial activities for a long time after the earthquake. To prevent disasters caused by such malfunctions, we need to be able to predict how the highway system will perform after the earthquake. To do this we need to do more than simply evaluate the earthquake resistance of each facility in the system by using information about the possible earthquake intensity, the local ground conditions, and the mechanical strength of the system structures. We need also to examine earthquake resistance from the viewpoint of whether or not the system will function after the earthquake [Shinozuka, Takada and Kawakami, 1977; Britz, Edelstein and Oppenheim, 1977; Longinow, Bergmann and Cooper, 1977; Hendrickson, Oppenheim and Siddharthan, 1980; Kawakami, 1982; Wakabayashi and Iida, 1995; Kameda, 1996; Nojima and Kameda, 1996]. Moreover, when designing the highway system, we should take into account the overall function of the system when we decide what the strength of each structure in the system should be [Kawakami, 1982, 1984].

Several approaches to examining the reliability and serviceability of systems subjected to an earthquake have been developed [e.g., Shinozuka, Takada and Kawakami, 1977], but most of them deal only with the probability of physical or functional failure, and do not provide any information on the post-disaster role of each structure in the system. This kind of information is important in determining not only the seismic design of each structure in the system but also the network configuration.

The purposes of the research described here were to develop a methodology for estimating the performance of highway network systems subjected to earthquakes and to develop procedures for characterizing the post-earthquake role of each road in the system. A Monte Carlo technique taking into account seismicity, ground conditions, and the strength of the structures in the system was used to simulate the physical damage to the highway system. A detailed method using flow analysis and taking into account the effects of the decreased capacity of the road after the earthquake was then used for examining the functional damage and the role of each road in the highway system. Lastly, these methods were used to evaluate the earthquake performance of the highway systems in Tokyo, Japan.

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OUTLINE OF METHOD

The evaluation algorithm that was used was one with four steps:

1. The failure probability of each road in the highway system is estimated giving due consideration to factors like seismicity, ground conditions, and the strength and characteristics of the component structures. This failure probability is then used, in a Monte Carlo technique, to simulate the decrease in the traffic capacity of each road.

2. Traffic demand after the earthquake is estimated with due regard to ordinary demand, emergency demand, etc.

3. The method of traffic assignment, applied to the highway system with the simulated capacity and demand, is then used to calculate the post-earthquake traffic flow.

4. This simulation is repeated many times in order to evaluate the functional reliability of the total highway system and the post-earthquake role of each road in the system.

ILLUSTRATION OF METHOD AND ASSUMPTIONS

Consider the simple highway system shown in Figure 1. It is composed of two major cities (nodes 1 and 2), trunk lines (links 1-3 and 3-2), and subsidiary lines (links 1-4 and 4-2).

The ordinary traffic flow before the earthquake was calculated under the following assumptions:

(1) Traffic demands in the normal operating state are assumed (Table l).

(2) Each driver chooses the fastest route and drives at 40 km/h.

(3) The ordinary traffic capacity of each link is twice as much as the distributed traffic volume (Table 2).

In applying the method to the real system, the assumptions that are made should be as detailed and realistic as possible. In the following, however, in order to illustrate mainly the effect of the network configuration, the following failure was assumed:

(4) The failure of the road occurs according to the postulates of a Poisson process. (Expected numbers of failures per kilometer, v, are 0.3 for link 1-3 and 0.05 for the other links.)

(5) The degree of damage, r, is defined by the following ratio:

r = 1-(traffic capacity after the earthquake)/(ordinary traffic capacity), (1)

which is an independent random variable distributed uniformly between 0 and l.

In simulating the traffic flow after the earthquake, the following assumptions were made:

(6) The traffic capacity of each link is equal to the lowest capacity at any of the damaged locations in the link. The capacity ratio is defined for each link as:

D=(traffic capacity after the earthquake)/(ordinary traffic capacity) (2)

(7) The relationship between the car velocity V and the traffic volume-capacity ratio K is that shown in Figure 2 [Public Works Research Institute, 1978].

K = (traffic volume)/(capacity) (3)

(8) Each driver chooses the fastest route.

(9) Although the traffic demand after the earthquake should be estimated for each stage of recovery, in this paper the traffic demand after the earthquake is assumed to be the same as that before the earthquake.

(10) Dijkstra's method and the incremental-assignment method are used to make the traffic assignment.

Figure 3 shows the relationship between the traffic volume-capacity ratio K and the reduced volume ratio G, given as [Public Works Research Institute, 1978]

G=(reduced traffic volume)/(ordinary capacity), (4)

obtained when the simulations of road failures and traffic assignment were repeated 50 times. In the normal operating state, the traffic volume-capacity ratio K is 0.5, and we know from Eq. 4 that the reduced volume ratio G is 0.

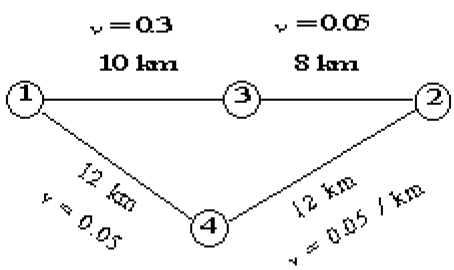

Figure 1: Simple highway system

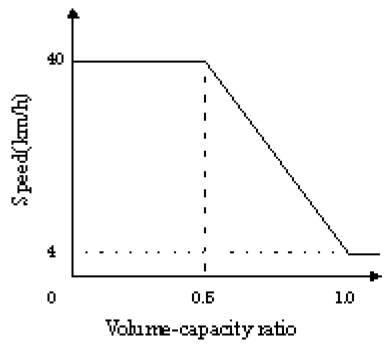

Figure 2: Relation between car velocity and volume-capacity ratio

Table 1: Traffic demand between nodes

Node no.	Node no. 1	2	3	4
1	0	560	140	100
2	560	0	190	100
3	140	190	0	0
4	100	100	0	0

Table 2: Ordinary traffic capacity

Link	Traffic capacity
1-3	1400
1-4	200
2-3	1500
2-4	200

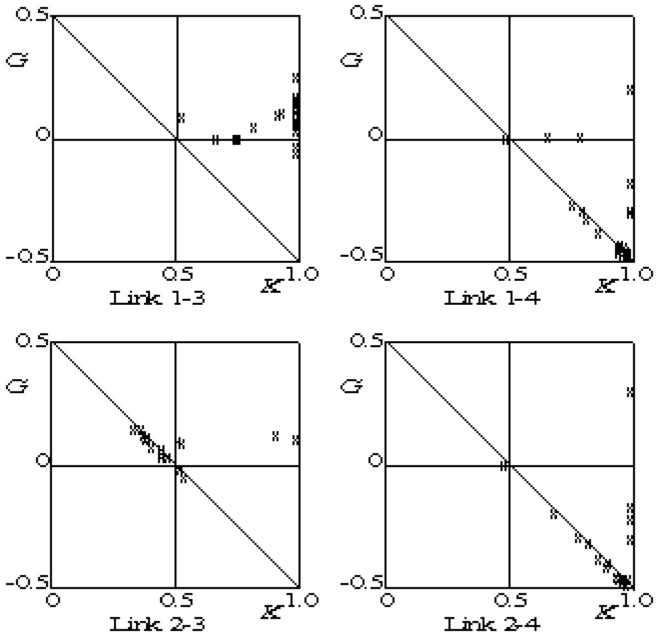

Figure 3: Distributions of ratios *K* and *G* for each link

EVALUATION OF ROLE OF EACH ROAD

As shown in Figure 3, the distribution patterns differ between links: plots of *G* versus *K* are largely distributed over the upper right quadrant for link 1-3; in the upper left quadrant for link 2-3; and in the lower right quadrant for links 1-4 and 2-4. These differences can be explained as follows:

Because link 1-3 is the most fragile (see the ν values in Figure. 1), the traffic capacity of link 1-3 decreases drastically after the earthquake, and the road is congested, which in turn means that the *K* value is increased. Drivers therefore take the long way round, and the reduced traffic volume in link 1-3 produces a positive *G* value. And the detour caused by the failure in link 1-3, which is connected in series to link 2-3, decreases the flow in link 2-3. This produces a decreased *K* value and a positive *G* value. This detour also causes congestion in links 1-4 and 2-4, even though these links are scarcely damaged. This congestion increases *K* values and makes *G* values negative.

HIGHWAY SYSTEM IN TOKYO

The above-mentioned techniques were applied to the highway system in Tokyo, Japan, and the earthquake performance of the whole system was evaluated as was the role of each road in the system. Traffic demands in the normal operating state were assumed based on the surveyed OD (Table 3). The assumptions 1-3 mentioned above were used, and the distribution of capacity in ordinary conditions was obtained as shown in Figure 4. The numbers of failures in assumption 4 were expected to be 0.5/km in all the links in Figures 5-7.

The distribution patterns of medians of each of three ratios, the capacity ratio *D*, the volume-capacity ratio *K* and the reduced volume ratio *G*, obtained from 100 simulations were compared in Figures 5-7. Figure 5 shows that the capacity ratio is large for short links, which are mainly distributed in the center of the city in the eastern side of Tokyo, and is small for long links. Figure 6 shows that the center of the city is not so congested as the suburban region. The reduced volume ratio in Figure 7 shows a little more complex result. However, it can be noticed that the distribution patterns of each of these three ratios are similar in spite of the much difference in the value ν, and all roads can be classified into one of three types as shown in Figure 8: (1) roads congested because of damage within it; (2) roads lightly traveled because of damage in other roads; and (3) roads congested because of damage in other roads. Based on the obtained results and the distribution of the surveyed ordinary volume-capacity ratio in Figure 9 the congestion in each road after the earthquake can be estimated.

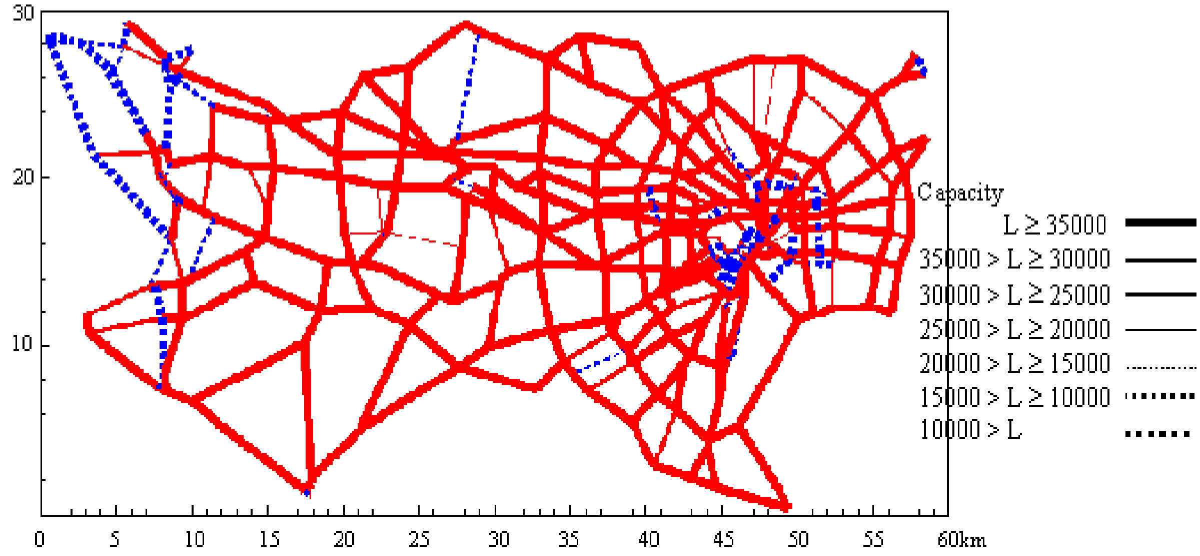

Figure 4: Assumed distribution of capacity in ordinary conditions

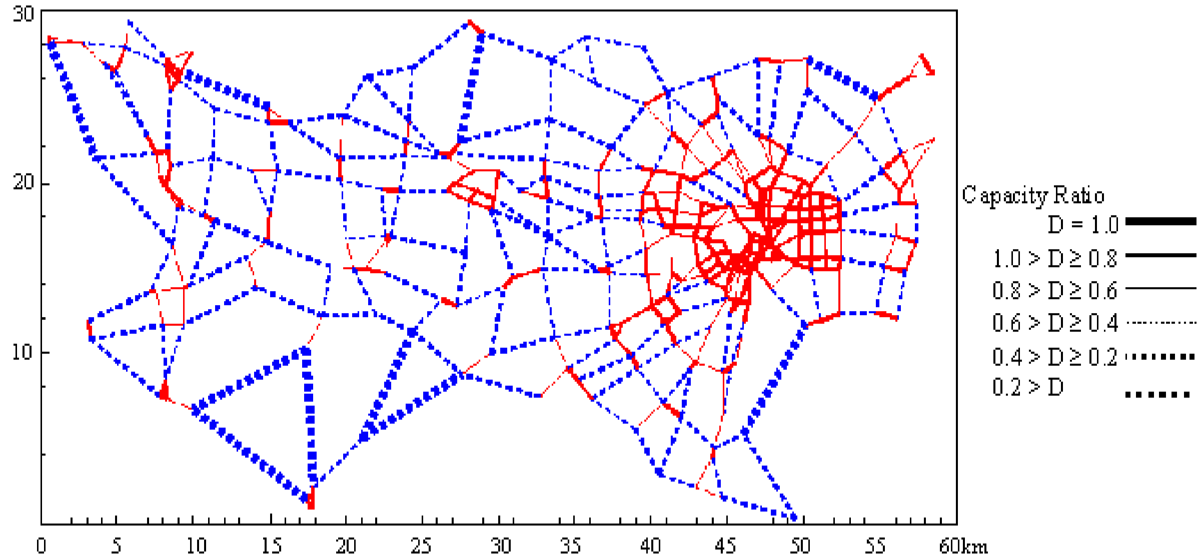

Figure 5: Distribution of medians of capacity ratio *D* in highway system in Tokyo (*ν*=0.5/km)

Table 3: Surveyed OD in and around Tokyo [Transportation committee, 1989]

	Tokyo(city)	Tokyo(suburb)	Kanagawa	Saitama	Chiba	Total
Tokyo(city)	3088609	148834	196374	231823	162940	3828580
Tokyo(suburb)	138396	1639523	115177	70196	5071	1968363
Kanagawa	178552	115835	4445686	14232	13856	4768161
Saitama	222485	70540	13793	3917220	39159	4263197
Chiba	153556	5548	13324	38498	3583693	3794619
Total	3781598	1980280	4784354	4271969	3804719	18622920

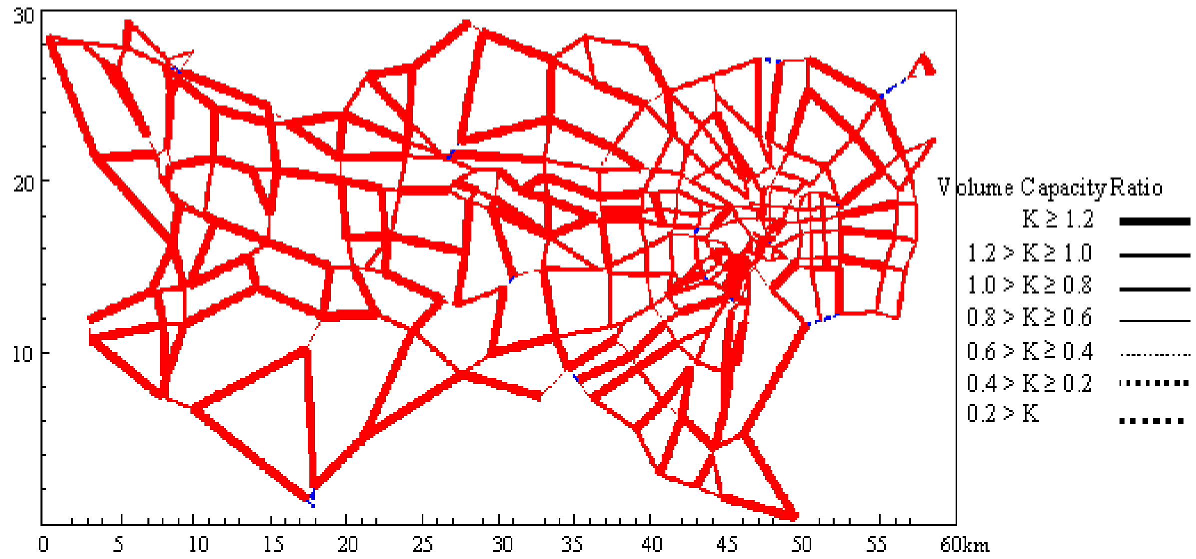

Figure 6: Distribution of medians of volume-capacity ratio *K* in highway system in Tokyo (*ν*=0.5/km)

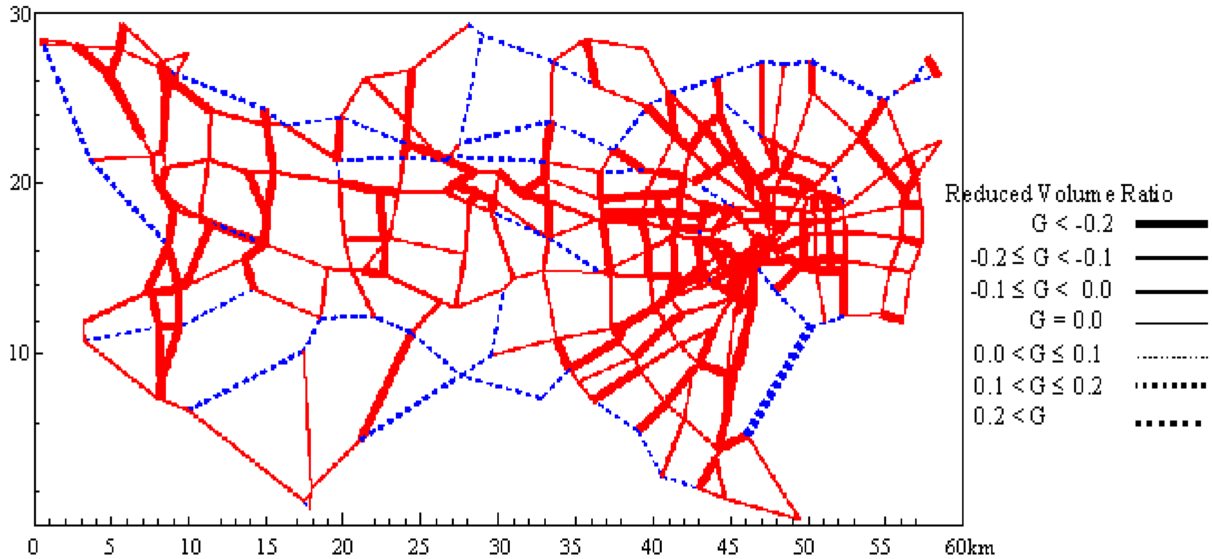

Figure 7: Distribution of medians of reduced volume ratio *G* in highway system in Tokyo (*ν*=0.5/km)

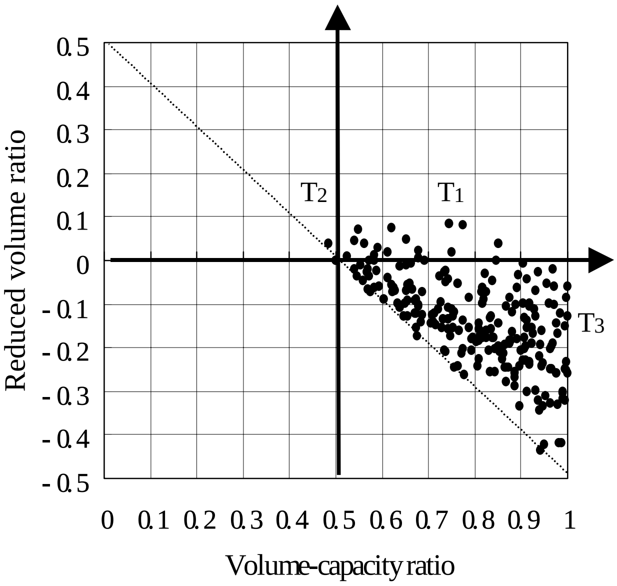

Figure 8: Distribution of medians of volume-capacity ratio *K* and reduced volume ratio *G*

Figure 9: Distribution of ordinary volume-capacity ratio in highway system in Tokyo

[Road transportation senses, 1990]

CONCLUSIONS

A Monte Carlo technique to simulate the post-earthquake performance of the highway network system has been described, and a detailed method using flow analysis to take into account the effects of the decreased capacity of the road after the earthquake has been described. These methods have also been used to evaluate the earthquake performance of the highway systems in Tokyo as well as the post-earthquake role of each road in these systems.

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