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PERFORMANCE EVALUATION METHOD OF HIGHWAY TRANSPORTATION SYSTEMS DURING POST-EARTHQUAKE PERIOD

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SUMMARY

In past earthquakes, malfunction of transportation systems caused ineffective post-earthquake restoration works, and affected daily lives and industrial activities. The purpose of the present study is to propose an evaluation method of performance of functionally disordered transportation systems after an earthquake. From the viewpoint whether a highway transportation system can fulfill its function after an earthquake, the results of this study can be utilized for practical seismic design purposes and for establishment of predisaster plans.

INTRODUCTION

Among various lifeline systems, the highway transportation system plays a very important role in expediting fire-fighting, relief works, and repair activities, by moving goods and people involved in these activities during post-earthquake period. Its functional failure would cause serious influence and economic loss in the area that sustains damage during the earthquake. On this account, some research has been devoted to investigate post-earthquke behavior of highway transportation systems.

However, its restoration process during post-earthquake period has been little studied in a practical sense. A highway transportation system bears the character of a network system which is organized by a number of elements. Therefore, when faced with the problem of post-earthquake restoration, not only its progress for each individual element but also that for the network system as a whole should be regarded as the main concern. It is difficult to make clear decisions regarding desirable countermeasures considering the complex system properties.

This paper presents a simulation method which permits practical evaluation of the post-earthquake recovery process of a highway transportation system. The simulation procedure comprises three phases: 1) Assessment of damage state of network, 2) Performance evaluation of system included in traffic flow analysis, and 3) Simulation of damaged network restoration. The present method is applied to evaluate the performance of highway transportation system in the Izu Peninsula (Shizuoka, Japan) during post-earthquake period related with restoration policy adopted.

FUNDAMENTAL CONCEPTS IN RESTORATION PROCESS SIMULATION

Modeling of Damage States Many kinds of damage modes are expected to occur in an earthquake, e.g., cracking of highway surfaces, embankment failures, slope failures, landslides, sliding down of embankments, and collapse of bridges. They could result in traffic malfunction causing impassabilities or decrease in number of lane.

In this study, a highway system is expressed as a network model, i.e., a combination of nodes and links. Moreover, a link is partitioned into some "segments", and a damaged spot is expressed by value of "damage level" given to each segment. To represent such damage states on two-lane highway, the damage level of segment k on link j, LS_{jk}, is defined as follows :

$$LS_{jk} = \begin{cases} 0 & \text{(No damage or minor damage)} \\ 1 & \text{(Damage state with one-way traffic)} \\ 2 & \text{(Damage state with suspension of traffic)} \end{cases} \qquad (1)$$

The damage level of link j is defined as

$$LL_j = \max_k (LS_{jk}) \qquad (2)$$

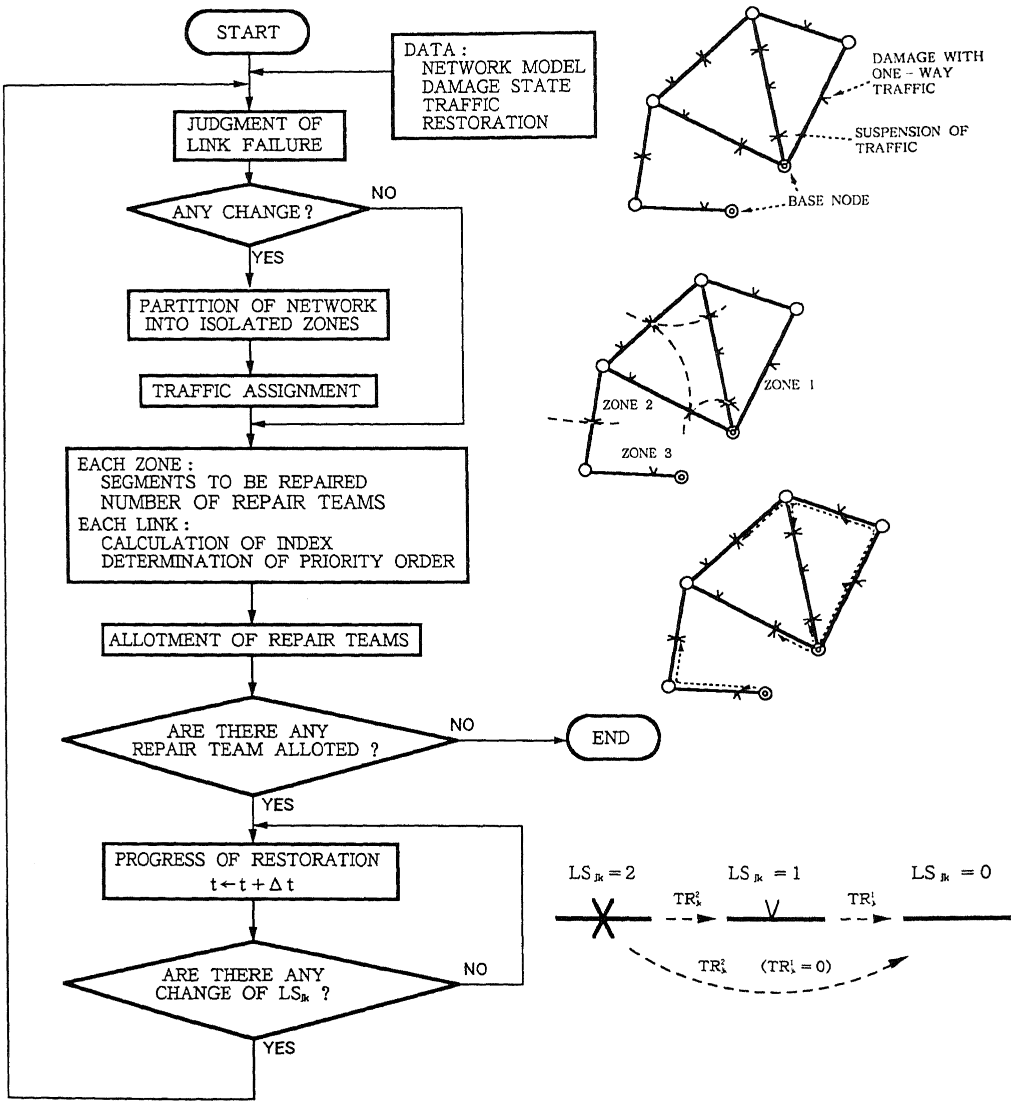

Fig. 1 Overall Flow Chart of Performance Evaluation Method of Highway Transportation System

The value of LL_j determines the functional fulfillment of link j.

Repair Works In this study, the restoration problem is separated into two categories, emergency restoration and rehabilitation works. The main consideration in the emergency restoration is recovery of connectivity between nodes, with the aim of elimination of isolated zones. The purpose of rehabilitation works, which usually follow emergency restoration stage, is to control daily traffic smoothly, and to improve traffic capacity of highway. Obviously, these two stages are not always separated.

There are many types of damage states, and each damaged spot would have different severity. Damage modes or damage levels can be roughly evaluated by the time required for restoration. Repair works are defined as improvement of damage level. (For example, $LS_{jk} = 2 \rightarrow 1 \rightarrow 0$) Time required for restoration is defined as follows :

For Segments with $LS_{jk} = 2$

TR^2_{jk} : Time required for the value of LS_{jk} to turn into unity as a result of repair works

TR^1_{jk} : Time required for complete restoration after the moment that the value of LS_{jk} turns into unity

For Segments with $LS_{jk} = 1$

TR^1_{jk} : Time required for the value of LS_{jk} to turn into zero.

$TR^2_{jk} = 0$

The combination of values for TR^2_{jk} and TR^1_{jk} will be determined corresponding to the damage mode of the segment.

Allotment of Repair Work Teams Restoration work demands manpower and materials, which often take the form of some teams. Hence, the concept of repair work team is introduced into the present simulation model. Restoration work is expressed by number of repair work team alloted to a segment (j,k), VR_{jk} (t). Each node is assumed to have ability to dispatch certain number of repair work teams to damaged spots. To simplify the problem, the nodes which can dispatch repair work teams are assumed to be limited. Such nodes are distinguished from other nodes, and are named "base nodes for restoration activity".

The following matters are assumed when the repair work teams are dispatched.

①The number of repair work teams for one damaged spot varies depending on its damage level. For example, in a numerical example mentioned later, the following are assumed : 1 for damaged level 1 ; 1 or 2 for damage level 2.

②Priority is given to impassablile segments ($LS_{jk} = 2$) in allotment of repair work teams.

③The damaged spots to which the repair work teams are dispatched, are confined to the extent that they can be reached through the passable links from the base nodes.

Restoration Policy Restoration policy is a basis for deciding where repair work teams should be alloted, or which damaged spots should be given higher priority, in the damaged highway transportation system estimated in a damage assessment procedure. The priority order of the damaged spots is determined based on some index : for example, order of damage severeness, order of traffic capacity, and order of usual traffic. After all, it must be sufficient to understand that a restoration policy designates the index considered as a basis. If there are too many damaged spots to which repair work teams are allowed to be alloted, they will be dispatched based on the priority order determined time by time, considering the number of available repair work teams.

Estimation of System Recovery In general, physical damage of structure and that of system performance do not agree with each other. Consequently, the "structural damage" and "functional damage" should be evaluated individually to monitor restoration progress. The structural damage can be evaluated by the number of damaged spots and links unrepaired, while the functional damage is considered based on the result of traffic assignment to the network system.

The following are considered as system performance indices :

①The decrease in total traffic after an earthquake from normal value, ΔQ

② Average running time, $\overline{T}$

③Converted traffic loss, $\Delta Q\overline{T}$

$$\Delta Q\overline{T} = \Delta Q + w\,(\overline{T} - \overline{T_0}) \tag{3}$$

where w is a properly evaluated weighting factor, and $\overline{T_0}$ is the normal value for $\overline{T}$.

DAMAGE SIMULATION OF HIGHWAY SYSTEM IN IZU PENINSULA

Data of damaged highway transportation system are required for the application of restoration simulation method. In order to obtain these data, the damage state of a network system is to be simulated.

<u>Highway System</u> The damage simulation is applied to highway network system in Izu Peninsula. The Izu peninsula is a appropriate example as a model, because the typical damage states or restoration process considered in the present evaluation method were observed during and after Izu-Oshima-Kinkai Earthquake of 1978 (Ref.1). The highway network is put into a simplified network model shown in Fig.2. There are 25 nodes and 38 links in the model. The length of each link is obtained from a roadmap, and that of every segment is 1km.

<u>Assumed Earthquake</u> Network damage is simulated under the assumption that an earthquake equivalent to the Izu-Oshima-Kinkai Earthquake and its main aftershock occur on the same region. It is reported that most of severe damage caused by the Izu-Oshima-Kinkai Earthquake was concentrated in the central portion of the Izu Peninsula (Ref.1), where the seismic intensity has been estimated to be V～Ⅵ (JMA scale).(Ref.2)

<u>Damage Modes</u> The following two types of failure are taken into account.

Damage Mode 1 :Damage states owing to obstructions on highway surfaces such as landslides, and fallen stones

Damage Mode 2 :Damage states with cracking or subsidence of highway surfaces, or collapse of embankments

Probability of damage occurence is assumed as shown in Table 1. It was estimated based on damage records after the Izu-Oshima-Kinkai Earthquake (Ref.4).

<u>Simulated Damage</u> A typical damaged nework generated by Monte Carlo simulation is shown in Fig.2. One of the most remarkable features of the damage due to the Izu-Oshima- Kinkai Earthquake is that the south portion of the Izu Peninsula was isolated from other regions. As far as such aspect of damage is concerned, this result shows

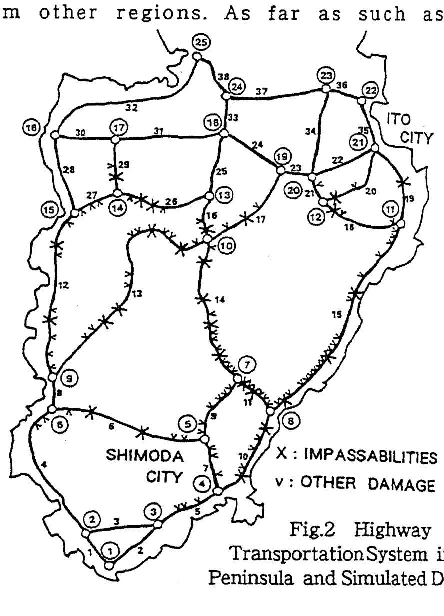

Fig.2 Highway Transportation System in Izu Peninsula and Simulated Damage

Table 1 Probability of Damage Occurence

Seismic Intensity \ Damage Level	Damage Mode=1		Damage Mode=2	
	1	2	1	2
Ⅳ	0	0	0	0
Ⅴ	0.10	0.08	0.10	0
Ⅵ	0.10	0.50	0.29	0.02

Table 2 Time Required for Restoration

Damage Level	Damage Mode=1			Damage Mode=2		
	1	2		1	2	
	TR^1_{jk}	TR^1_{jk}	TR^2_{jk}	TR^1_{jk}	TR^1_{jk}	TR^2_{jk}
Upper Limit (days)	1	4	5	5	0	20
Lower Limit (days)	0	1	0	1	0	5

fairly good agreement with the damage record.

APPLICATION OF PERFORMANCE EVALUATION METHOD TO HIGHWAY SYSTEMS IN IZU PENINSULA

Conditions and Restoration Policies Assumed   Generally, severe damage requires long period for the restoration. The failure with damage mode 1 will be able to restore in a relatively short time, while it may take considerable time to restore if a damage with mode 2 occurs. In the present study, the upper and lower limits for distribution of restoration time are assumed based on this idea, related to some restoration work records (Ref.4). Table 2 shows the upper and lower limits of time required for restoration corresponding to each damage mode and damage level. Values for TR^{l}_{jk} $(l = 1,2)$ are obtained by random simulation method, based on these data.

It is assumed that the activity base nodes are node 21 (Ito-city) and node 4 (Shimoda-city). Each base node is allowed to dispatch 3 repair work teams at most. The following restoration policies are adopted to give the priority order :

Restoration Policy 1 :Higher priority is given to links which require shorter time for restoration
Restoration Policy 2 :Higher priority is given to links which require longer time for restoration
Restoration Policy 3 :Order of usual traffic flow on link
Restoration Policy 4 :Order of link flow (for impassable links, order of usual link flow)
Restoration Policy 5 :Order of (usual link flow) / (total time for restoration)
Restoration Policy 6 :Order of traffic capacity of link (for links which have equal traffic capacity, order of usual link flow)
Restoration Policy 7 :Mixed policy which includes policy 1 (until the elimination of isolated zones) and policy 3 (after the elimination)

Results and Discussions   Figure 3 shows a typical result for period and restoration order of damaged links, where policy 1 is adopted. Figure 4 shows the influence of restoration policy on the progress of physical restoration : time variation of the total number of damaged links which remain unrepaired, the number of impassable links, the total number of damaged spots, and the number of impassabilities. It is found that every policy requires about 50 days for the complete restoration. Almost every restoration policy makes little difference in the number of damaged spots. However, it must be mentioned that system performance indices, ΔQ, $\overline{T}$ and $\Delta Q\overline{T}$, vary evidently with respect to restoration policy, as indicated in Fig.5.

Restoration policy 5 is found to induce the fastest elimination of ΔQ. Policies 1 and 7 also should be noted for the decrease in ΔQ. It must be proper to regard ΔQ to represent degree of isolation among nodes with weights of node traffic generation. Since policies 1 and 5 are for the purpose of elimination of impassable links, the effect of the recovery of connectivity among nodes is brought. Restoration policy 2 seems to

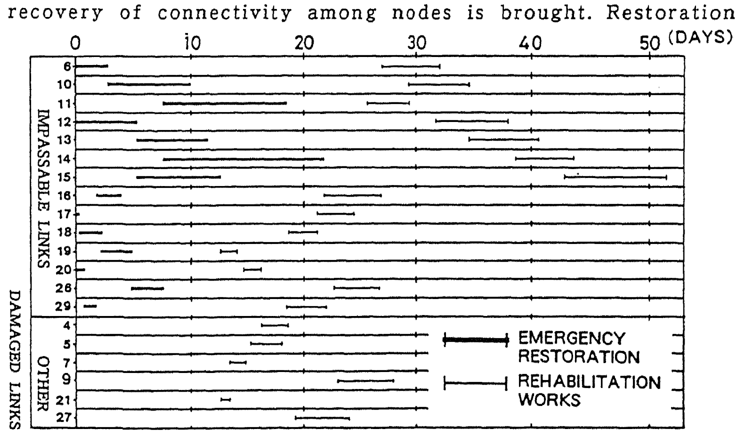

Fig.3 Periods of Emergency Restoration Stage and Rehabilitation Work Stage Simulated with Restoration Policy 1

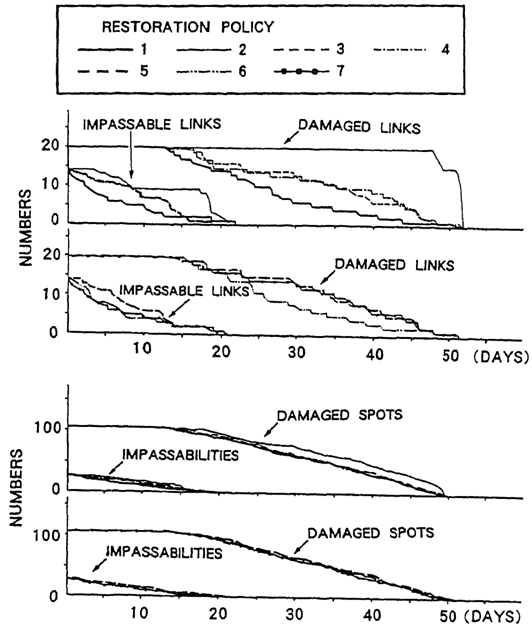

Fig.4 Restoration Progress in Structural Damage

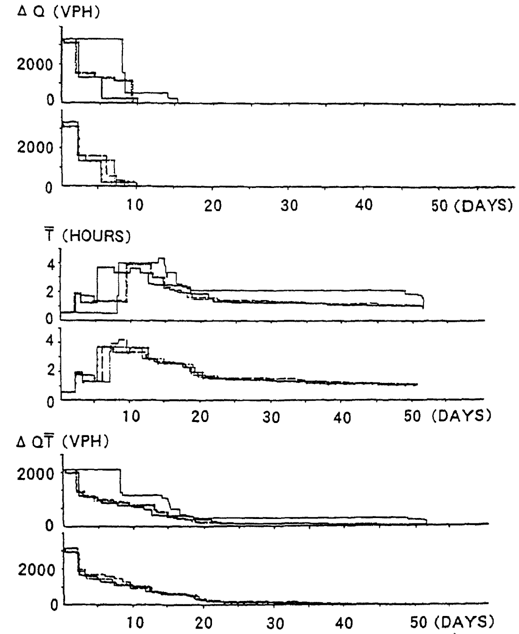

Fig.5 Progress of System Performance Recovery

be the worst one from a functional point of view. Policies 3 and 4 are intended for favorable recovery of transportation performance, and are working pretty well in the period of 15～22 days after the damage. Nevertheless, it cannot be concluded that they are superior to policy 1 or 7 even in the system performance as a whole. This result indicates that traffic volume alone is not an effective basis for making decisions on restoration of a system.

CONCLUDING REMARKS

Time variation of link flow, which is not shown in this paper, has also been calculated. Nice distinctions were shown in traffic state correlated with restoration policy adopted. It was found that traffic volume markedly increases on some roads. The reason for this result is considered as follows : 1) Much traffic pours into the roads, 2) Temporary traffic congestion occurs, and spreads wide, and 3) It relaxes as the time proceeds. Though effective on the whole in mitigating degree of traffic congestion, adopting a single countermeasure which does not depend on time involves some prolongment of traffic disorder. From this point of view, it is very important to predict the influence of alteration of restoration policy on the establishment of predisaster plans.

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