Highway Network Performance Analysis under Seismically Induced Traffic Delays

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1. Introduction

The highway system is one of the most vital networks in urban area. It works not only for the welfare of the general public but also for the commercial, industrial and cultural activities. However, it shows that the highway systems were damaged by earthquakes. It caused not only severely disrupt traffic flows but also negative impact on the economy of the region as well as post-earthquake emergency response and recovery. Highway transportation systems are complex with many engineered components and placed in equally complex natural environments. Among the engineered components of highway network system, bridges represent potentially the most vulnerable structural components under earthquake conditions.

In this study, the new methods for evaluating the performance of highway network systems under the severe earthquake conditions are developed. And as an example analysis, the numerical simulation is carried out to the Los Angeles highway network system to demonstrate the efficacy of the methods. States of the network damage under scenario earthquakes are evaluated by means of Monte Carlo simulation techniques utilizing the fragility curve for individual bridges. And the method for evaluating the seismic risk of the network is developed by integrating the seismic hazard represented by the scenario earthquakes. System performance reduction is measured in terms of a rather simplistic index "drivers' delay" that is calculated by equilibrium analysis of transportation systems considering detours.

2. Modeling Seismically Damaged Highway Network

Fragility curves are utilized to generate, in Monte Carlo simulation, the state of damage for each and every bridges on highway network systems. For Monte Carlo simulation, random numbers, which are uniformly distributed between 0 and 1, are generated for every bridge. According to this random number, the damage states of each bridge are evaluated.

The State of bridge damage is quantified using "Bridge Damage Index (BDI)" as shown in Table 1.

Table 1

Damage State	BDI
Minor Damage	0.1
Moderate Damage	0.3
Major Damage	0.75
Collapse	1.0

To utilize damage states for equilibrium analysis, the state of link damage is quantified by making use of "link damage index", LDI which is computed for each link as SRSS (the square root of the sum of the squares) of BDI values assigned to all bridges on the link under consideration.

$$LDI_l = \sqrt{\sum_{j=1}^{N} (BDI_j)^2}$$

LDI: link damage index on link *l*
N: total number of bridges on link *l*
BDI: Bridge damage index, bridge *j* on link *l*

In the analysis of post-earthquake traffic flow, the alternate routes are considered to possess lesser traffic capabilities in terms of both free flow speed and capacity compared with those associated with the segment or the link of the expressway they replaced. Table 2 shows changes in road capacity and free flow speed. Values account for the changes resulting from the repair work, and not necessarily from the detour of traffic.

Table 2

Damage State	LDI	Capacity Change Rate	Free Flow speed Change Rate
No Damage	LDI<0.5	100 %	100 %
Minor Damage	0.5≤LDI<1.0	100 %	75 %
Moderate Damage	1.0≤LDI<1.5	75 %	50 %
Major Damage	1.5≤LDI	50 %	50 %

The current analysis applies a summary index of system performance degradation based on drivers' travel time delay, which is estimated based on post-earthquake network topology relative to pre-earthquake intact condition. Drivers' delay is developed by utilizing user optimizing deterministic assignment. In this study, to carry out the analysis numerically, the incremental assignment method is used.

$$l = \sum_a x'_a t'_a(x'_a) - \sum_a x_a t_a(x_a)$$

$t_a(x_a)$: the travel time on link *a* in intact network
x_a: the flow on link *a* in intact network
$t'_a(x'_a)$: the travel time on link *a* in damaged network
x'_a:the flow on link *a* in damaged network

Methods for assessing earthquake loss estimation measures are necessarily probabilistic, in view of the indeterminacy of future earthquake event. However,

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evaluating for all possible earthquakes is generally impractical. Instead, the methodology identifies a small set of earthquake events, Q_j ($j=1,2,\ldots M$), where $M<<N$, together with probabilities p_j such that

$$\sum_{j=1}^{M} \overline{p_j}(\overline{Q_j}) \approx \sum_{i=1}^{N} p_i(Q_i)$$

M: the number of possible earthquakes that produce hazard level h in the small set
N: the number of possible earthquakes that produce hazard level h
Q_j: jth selected earthquake event
P_j: annual probability of jth selected earthquake event
Q_i: ith event of possible earthquake
P_i: annual probability of ith event of possible earthquake

Specifically, the small set of events Q is to be selected in order to represent different levels of system performance or system damage state S. The p_j can be considered as "hazard-consistent probabilities", they fully represent the local hazard curve.

This method constructs a "system risk curve" that denotes the probability of exceedance for various levels of highway network performance degradation.

These results pertain to the case without seismic hazard mitigation. A similar curve can be developed for the "with-mitigation" case if bridge fragility curves are revised to indicate the effects of seismic upgrading.

3. Application to Los Angeles Highway System

The study area is limited to Los Angeles County and Orange County in the Los Angeles Metropolitan Area. This network consists of 118 nodes and 185 links. The total number of bridges is 2727.

Fragility curve[1)] for application to the bridges of the Los Angeles freeway network are constructed (M. Shinozuka et al. 1997) on the basis of damage data reported by Caltrans (State of California, Department of Transportation) engineers for 1998 bridges damaged in the 1994 Northridge Earthquake.

Origin-Destination data for Los Angeles highway network is generated from 1991 Southern California Origin-destination Survey (SCAG). In this case study, 47 scenario earthquakes[2)] are selected, such as Elysian Park MCE Event, for the region of Los Angeles County and Orange County in California. 47 sets of PGA are generated from the 47 scenario earthquakes by USC-EPEDAT. Average of drivers' delay and hazard-consistent probabilities for each scenario earthquake allow the L. A. highway system's risk of earthquake-induced performance degradation to be succinctly described in a system risk curve, as shown in figure 3. The system risk curve[2)] for Los Angeles metropolitan area highway network as a function of the minimum distances between all the OD pair but ignoring the change in flow and capacity has the same trend as the system risk curve based on the equilibrium traffic analysis. However, the system risk curve using equilibrium traffic analysis shows that the slope of the curve changes more sharply than the system risk curve using distances at 2% probability of exceedance.

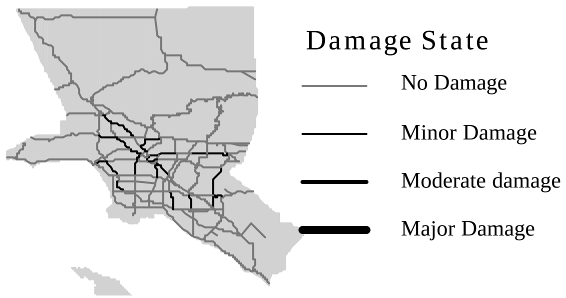

Figure 1

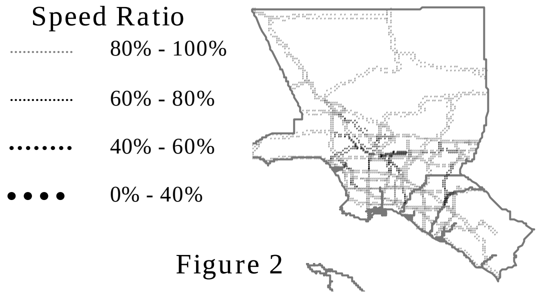

Figure 2

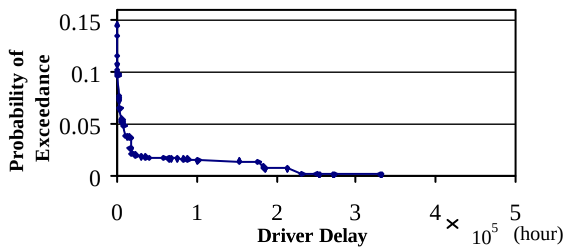

Figure 3　　Elysian Park M7.1 Result

4. Conclusion

Major findings are as follows,

1. BDI and LDI are developed by utilizing Monte Carlo simulation techniques.
2. System performance degradation can be expressed in terms of drivers' delay which is developed by network equilibrium analysis.
3. Network equilibrium analysis shows bridge damage affects the vehicles flow on both the link carrying the damaged bridges and the other links.
4. A method of regional seismic risk analysis for a highway network system is developed on the basis of a number of scenario earthquakes representing the seismic hazard of the region in which the highway network is located.

The system risk curve can be developed by integrating the estimation of bridge damage state. Results could be used in assessing the benefit-cost analysis of the proposed mitigation measures.

Reference

1) M. Shinozuka, 1998, Development of Bridge Fragility Curves, Proc. of the Joint US-Italy Workshop on Seismic Protective Systems for Bridges, New York: Colombia Univ., April 26-28
2) Chang S. E., M. Shinozuka, Probabilistic Earthquake Scenarios: Extending Risk Analysis Methodologies to Spatially Distributed Systems, The Earthquake Spectra "forthcoming".