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지진 위험도를 고려한 도로 교통망의 내진보강 우선순위 결정

Retrofit Prioritization of Highway Network considering Seismic Risk of System

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국문 요약 >> 본 논문은 캘리포니아지역에 위치한 고속도로망을 대상으로 하여, 도로망내에 있는 교량의 내진보강 우선순위를 결정하는 방법에 관한 연구이다. 내진보강 우선순위 결정은 지진공학 분야에서 매우 중요한 이슈 중의 하나이며, 정부나 도로 관리청의 의사결정권자는 예산 배정 과정에서 이와 같은 문제에 항상 직면하게 된다. 본 연구는 특정지역의 고속도로망을 대상으로 어떻게 내진보강 우선순위를 결정할 것인가에 관한 방법론을 보여주고 있다. 우선순위 결정을 위하여 구조물의 지진 취약도, 도로망상에 위치한 각각 연결로의 중요도에 대한 개념이 먼저 소개되었다. 도로망상 각각의 교차로를 잇는 연결로를 지진 보강의 대상 단위로 하여 도로망의 내진 성능에 대한 시뮬레이션을 수행하였으며, 추가 소요되는 교통 지체시간을 각각의 시뮬레이션 경우에 대하여 측정함으로써 내진보강에 의한 효과를 평가하였다. 또한, 지진 위험도의 확률적인 특성을 반영하기 위하여 확률론적 시나리오 지진을 도입하였다. 본 연구의 결과에서 알 수 있듯이 우선순위의 의미는 이해관계자의 주요 관심 사항에 따라 다르게 정의될 수 있고, 각각 다른 우선순위 결과를 보여주게 된다. 본 연구는 교통망의 효과적인 내진보강을 위한 우선순위 결정 과정에 도움이 될 수 있는 일반적인 지침을 제공할 것으로 기대된다.

주요어 교통망, 지진 위험도, 내진보강, 우선순위, 취약도 곡선

ABSTRACT >> This research focuses on the issue of seismic retrofit prioritization based on the Caltrans' highway network serving Los Angeles and Orange counties. Retrofit prioritization is one of most important problems in earthquake engineering, and it is a problem that most decision makers face in the process of resource allocation. This study demonstrates the methods of prioritized resource allocation in the process of retrofitting a regional highway network. For the criteria of a retrofit ranking, seismic vulnerability and the importance of network link are first introduced. Subsequently, link-based seismic retrofit cases are simulated, investigating the effects of the seismic retrofit in terms of seismic performance, such as driver's delay. In this study, probabilistic scenario earthquakes are used to perform a probabilistic seismic risk analysis. The results show that the retrofit prioritization can be differently defined and ranked depending on the stakeholders. This study provides general guidelines for prioritization strategy for the effective retrofitting of a highway network system.

Key words transportation network, seismic risk, retrofit, prioritization, fragility curve

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1. INTRODUCTION

Past experience showed that earthquake damage to highway components (e.g., bridges, roadways, tunnels, retaining walls, etc.) can severely disrupt traffic flows and thus negatively impact on the economy of the region as well as post-earthquake emergency response and recovery. Furthermore, the extent of these impacts will depend not only on the nature and magnitude of the seismic damage sustained by the individual components, but also on the mode of functional impairment of the highway system as a network resulting from physical damage of its components. However, because the application of retrofitting to all components in highway system is extremely costly and time consuming, overall improvements of existing road facilities are impractical.

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In addition, because of time and financial limitation, prioritized retrofitting in a highway system should be considered for effective implementation. Therefore, prioritization for upgrading of network components is essential consideration in the view of resource allocation with limitation. Generally, decision makers face this kind of prioritization problem such as selection of only several bridges in the overall network system.

Many researches have been conducted to develop efficient prioritization techniques for highway system with different goals to be achieved. These prioritization techniques provide a rational ranking among many bridges in order to indicate critical and important components. Kawashima et al.(1) and Nielson et al.(2) presented the prioritization methods using seismic vulnerability of bridges such as fragility curves. FHWA (Federal Highway Administration)(3) and Basoz et al.(4) also carried out ranking procedure based on the sum or multiply of different factors related to seismic hazard, structure fragility, and cost of failure. In addition, Chang et al.(5), Nuti et al.(6), Werner et al.(7), and Na et al.(8) developed analytical procedure for retrofit priority based on transportation network analysis.

It is a matter of fact that different views of stake holders and different goals of the retrofit result in different ranking of prioritization. Therefore it is difficult to establish the absolute best solution to decide ranking. The goals to be achieved should be clearly defined before decisionmaking for retrofit. Depending on the goals such as safety level, minimum cost, minimum driver's delay after an earthquake, each analysis leads to different upgrading priorities. In this study, two different sets of goals such as seismic vulnerability and importance of transportation network links are considered for the prioritization.

Prioritization is a kind of optimization problem and has been widely used for various purposes. For the highway system, most cases, seismic hazard at the location of bridge, bridge vulnerability, and cost of failure are considered as the form of sum or multiply of these factors. These factors which represent the goals of the stake holders correspond to objective function of optimization. These factors of criteria can be categorized as vulnerability and importance of bridge and are shown in Figure 1.

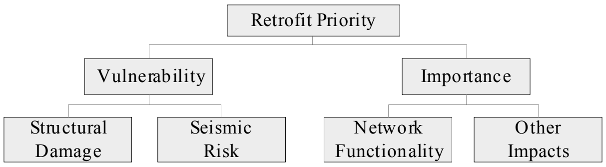
The purpose of this paper is to present the seismic retrofit priority of bridges based on the transportation network analysis and probabilistic scenario earthquakes. For the application, highway network system in the Los Angeles and Orange Counties is used. Based on the transportation network analysis, the prioritization procedure is presented.

2. SEISMIC PERFORMANCE EVALUATION OF HIGHWAY NETWORK

2.1 Highway Network: Spatially Distributed System

Highway network is a typical spatially distributed system whose components are located in a relatively wide geographical region but functionally interconnected to fulfill the supposed functionality of the system. Bridges, roadways, tunnels and some other structural components are linking and working together to transport vehicles (passengers and cargo) from one place to another, and the location of the components, are scattered.

Regarding seismic risk analysis of a spatially distributed system, the system's seismic performance should be emphasized under damage states of all its components.(9) The relationship between the system performance and the states of the components may be very complex and cannot be expressed explicitly in a mathematical equation. The system performance may be below its normal level even out of operation due to the seismic damage of its components. Additionally, in this kind of seismic risk analysis, the prediction/simulation of the states of its component and further the system performance evaluation should be scenario-based to reflect the spatial distribution of ground motion and be meaningful in the evaluation of the system performance. The overall process of this network analysis follows the flowchart shown in Figure 2.



〈Figure 1〉 Components in risk assessment for retrofit priority

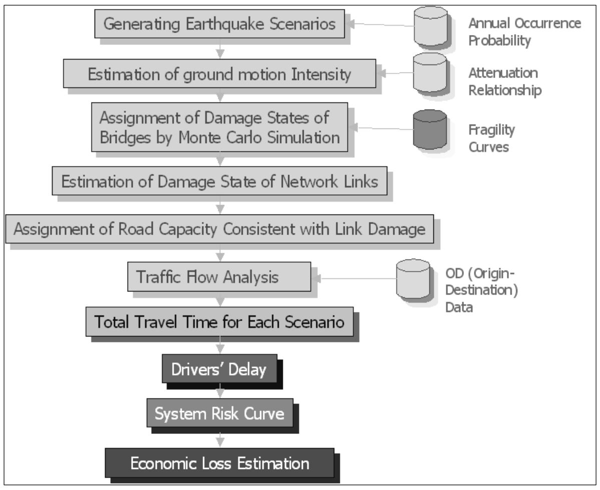
2.2 Seismic Hazard Modeling

In a region with high seismicity and a number of active seismic faults, such as Los Angeles Area, there are numerous possible earthquakes in the future. To perform a probabilistic seismic risk analysis, the probability of these events should also be quantified. In this study, the concept of probabilistic scenario earthquakes, in which a small set of scenario earthquakes with properly “assigned” annual occurrence probabilities are selected to approximate represents the regional probabilistic seismic hazard and is used for probabilistic risk estimation of spatially distributed systems. In this framework, expected loss can be written as below.

$$R_{Annual} = \sum_{i=1}^{N} L(S \mid Q_i) p_i(Q_i) \approx \sum_{j=1}^{M} L(S \mid \overline{Q_j}) \overline{p_j}(\overline{Q_j}) \qquad (1)$$

Where N = total number of possible earthquakes, $L(.)$ = Loss function, S = system performance, Q_i = i th possible earthquake, $p_i(Q_i)$ = annual probability of i th possible earthquake. Total number of possible earthquakes N may be quite large, particularly in high seismicity areas. So, a small set of representative earthquakes events $\overline{Q_j}$ is selected with probabilities $\overline{P_j}(\overline{Q_j})$, where $M << N$.

Particularly, 47 scenario earthquakes representing the regional seismic hazard in Los Angles and Orange County are used in this study.(10) This set of probabilistic scenario earthquakes is used as hazard input in evaluating the probabilistic seismic risk of highway network. For each of the 47 scenario earthquakes mentioned above, attenuation relationship of ‘Campbell’ is used to estimate site peak ground acceleration (PGA) for all the bridges of the system.



〈Figure 2〉 Flowchart of the Network Analysis

2.3 Transportation Network Model

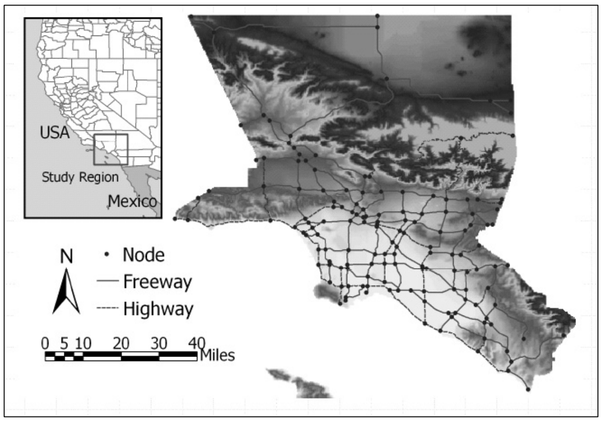
Like any highway system, the Caltrans’ highway transportation system in Los Angeles and Orange Counties is modeled as a network which combines a series of nodes and links. Each link represents a roadway segment which connects to any other segment at a point called node. In each link, there may have 0 to several bridge components. Figure 3 displays the freeway and state highway network for Los Angeles and Orange Counties, including 3,133 bridges. This network consists of 231 links.(11),(12)

In each link, only bridge component is assumed to be seismically vulnerable. Therefore, the damage states or performances of the bridges in one link directly relate to the link’s post-event performance. Link damage is represented by the worst state of damage of the bridges on that link (bottle-neck hypothesis). The link performance is determined by

$$t_a = t_a^0 \left[1 + \alpha \left(\frac{x_a}{C_a} \right)^{\beta} \right] \qquad (2)$$

where t_a =the travel time at flow x_a on link a, x_a = the flow on link a, t_a^0 = the travel time at free flow on link a, C_a = the “practical capacity” of link a, and α and β = parameters (α =0.15 and β =4.0 are typically used).

The origin-destination (OD) data used in this paper



〈Figure 3〉 Caltrans’ Highway System in LA and OC consist of 1996 southern California origin-destination survey data for 3217 traffic analysis zones (TAZ). Total travel time (t_{total}) can be expressed as

$$t_{total} = \sum_{a} x_a t_a(x_a) \tag{3}$$

where x_a = flow of link a and t_a = travel time of link *a*.

The analysis applies a comprehensive index of total transportation cost (drivers' delay), λ, based on post-earthquake network topology relative to pre-earthquake intact conditions. Drivers' delay is defined as

$$\lambda = t'_{total} - t_{total} = \sum_{a} x'_a t'_a(x'_a) - \sum_{a} x_a t_a(x_a) \tag{4}$$

where x_a = flow on link a in intact network (pre-earthquake), t_a = travel time on link a in in-tact network (pre-earthquake), t'_{total} = total travel time in damaged network, x'_a = flow on link a in damaged network (post-earthquake) and t'_a = travel time on link *a* in damaged network (post-earthquake).(11)

3. RETROFIT PRIORITIZATION IN HIGHWAY NETWORK

To decide retrofit strategy, link-based network analyses are conducted. As what can be indicated in Figure 4, link performance depends on the performance of bridges in that link. It means the state of link damage corresponds to the state of worst bridge damage in each link.(13-15)

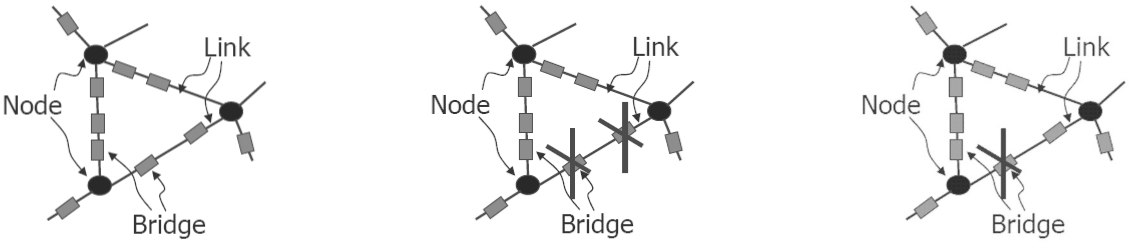
Conceptually, seismic priority index (SPI) of each link can be introduced as a function of seismic vulnerability V_n corresponding to fragility functions of each link *n* and seismic importance I_n. It can be expressed as below.

$$SPI_n = f(V_n, I_n) \tag{5}$$

In this study, first, two different factors are considered in risk assessment for an individual link. Firstly, “Seismic vulnerability” depends on the inherent characteristics of the structures and on local seismicity. In other words “vulnerability” is a function of the structural properties of the bridge and the site hazard. And then, “importance” of each link depends on the various issues such as transportation functionality, evacuation route, and regional economy. In this study, transportation network functionality represented by driver’s delay immediately after the earthquake is considered for the importance of network link.

3.1 Seismic Vulnerability of Each Network Link

Given the scenario earthquake, the 3,133 bridges in Los Angeles and Orange Counties are assigned their respective PGA at each site. This PGA directly relates to the damage states of each bridge. If the composite fragility curves representing all bridges in network system are used for the network analysis(16), the sum of maximum PGA values($\overline{PGA_{jn}}$) sustained by the bridges located in each link *n* for all scenario earthquakes (*j* = 1,2,.. ,*M*) can be translated to the seismic vulnerability of each link. The seismic vulnerability of each link *n* can be written as equation (6) and the results are shown in Table 1. I_{damage} corresponds to the index representing the probability of damage obtained from the fragility curves. It can be the sum of probability of each damage level (minor, moderate, major, collapse, etc) with a certain parameter. Because the composite fragility curves, representing damage levels of all bridges in network system with one set of fragility curves, are used in this



(a) (b) (c)

〈Figure 4〉 Trnasportation network for (a) pre-earthquake state, (b) and (c) damaged states after-earthquake

〈Table 1〉 Rank of Seismic Vulnerability of Each Link

Rank	V_n	Link ID	Rank	V_n	Link ID
1	0.030	4	6	0.025	9
2	0.029	12	7	0.024	116
3	0.027	142	8	0.023	118
4	0.026	5	9	0.023	119
5	0.026	141	10	0.022	92

study for a simple analysis, the same value of I_{damage} is applied for all link as 1. If the fragility characteristics of each bridge are known and can be applied in the network analysis, more accurate result can be obtained.

$$V_n = \sum_{j=1}^{M} \overline{PGA_{jn}} \cdot \overline{p_j}(\overline{Q_j}) \cdot I_{damage} \qquad (6)$$

3.2 Importance of Network Link

Seismic importance, I_n represented by the driver's delay, is obtained from the transportation network model runs. When the earthquake happens, transportation network system experiences various degree of damage so network capacity results in low-functionality. To evaluate the ranking of a certain link in the view of I_n, the considered link is assumed as fully damaged at each computational run like Figure 5. Then, the traffic flow under the damaged system is obtained. Through measuring the differences of traffic flow between two cases of intact condition (no damage on any of all links) and damaged condition (fully damaged on a certain link), the increased transportation cost such as driver's delay can be evaluated. After obtaining the traffic flow values for all links, it can be compared to consider the priority of each link. A higher driver's delay represents the higher importance.

〈Table 2〉 Rank of Seismic Importance of Each Link

Rank	Driver's delay (hr)	Link ID	Rank	Driver's delay (hr)	Link ID
1	1,026,842	125	6	11,686	121
2	91,592	98	7	10,737	141
3	66,545	24	8	10,087	203
4	61,546	31	9	8,561	135
5	22,325	44	10	8,444	202

Table 2 lists the results for 10 links with high importance index.

Using the results obtained in this step, one can indicate that which link is economically more significant than others and it can be useful information for decision makers who are in charge of resource allocation for the retrofit priority of the links and bridges on the highway network. However, even though this analysis shows the importance level of each link in the view of the network performance, it does not include the hazard level of each link. Namely, it can be happened that a certain link show very high seismic importance under the damaged condition of this specific link but it has very low possibility of damage because it is located in low seismicity area compared with other links. So combined concept with seismic vulnerability and importance needs to be introduced.

3.3 Retrofit Simulation Considering Seismic Vulnerability and Importance of Link

To provide the rational ranking of network link, computational transportation network analyses are conducted repeatedly with different scenario earthquakes (47 earthquakes) and different retrofit conditions. To simulate the retrofit condition of each link, very high median values in

〈Figure 5〉 Examples of Assumed Network with a Certain Damaged Link (for two cases) fragility parameters are assigned for a specific link at each run. Simultaneously, for all other links, the median values of empirical fragility curves developed by Shinozuka et al.(16) are assumed but '0' lognormal standard deviation is assigned to clearly distinguish the seismic vulnerability of each link and decrease the computational runs.

To evaluate the effect of retrofit of a certain link and provide the retrofit rank, the considered link is assumed as retrofitted at each computational runs and survived at any earthquake scenarios. Then, the traffic flow under each simulation model is obtained. Through measuring the differences of traffic flow between two cases of no-retrofit condition and retrofit condition of a certain link, the decreased driver's delay can be evaluated. This procedure is repeated for 47 scenario earthquakes and 231 links of transportation network considered in this study. Table 3 lists the results for 10 links with high index. This index of each link is obtained from the sum of driver's delay under each scenario earthquake × annual probability of corresponding earthquake.

4. CONCLUSIONS

This study concentrates on the evaluation of seismic prioritization for the retrofit on the Caltrans' bridges on the Freeway network in the Los Angeles and Orange Counties. This kind of prioritization problem is very important issue under limited resources and time. To demonstrate the seismic retrofit ranking of each link in the network, system analyses are conducted considering the network performance after earthquakes. In this study, seismic vulnerability and importance of each link are considered as the main components for the retrofit ranking. Additionally, retrofit simulations for each link considering combined multi-criteria including seismic vulnerability and network performance are conducted. The results obtained in this study can be useful to decide the rank for the retrofit prioritization and this analysis procedure can provide the valuable guidelines for the stake holders related to highway network system. Future study should be performed in the improvement of the modeling of network, considering more accurate fragility curves of bridges and total costs related to the restoration period of system network.

〈Table 3〉 Rank of Seismic retrofit based on combined criteria

Rank	Index	Link ID	Rank	Index	Link ID
1	103.69	125	6	44.10	174
2	91.63	92	7	42.64	143
3	83.42	141	8	40.84	21
4	69.94	9	9	39.69	24
5	49.94	119	10	38.29	116

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