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Reliability-based Life Cycle Cost Analysis for Optimal Seismic Upgrading of Bridges

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ABSTRACT

This study is intended to propose a systematic approach for reliability-based assessment of life cycle cost (LCC) effectiveness and economic efficiency for cost-effective seismic upgrading of existing bridges. The LCC function is expressed as the sum of the upgrading cost and all the discounted life cycle damage costs, which is formulated as a function of the Park-Ang damage index and structural damage probability. The damage costs are expressed in terms of direct damage costs such as repair/replacement costs, human losses and property damage costs, and indirect damage costs such as road user costs and indirect regional economic losses. For dealing with a variety of uncertainties associated with earthquake loads and capacities, a simulation-based reliability approach is used. The SMART-DRAIN-2DX, which is a modified version of the well-known DRAIN-2DX, is extended by incorporating LCC analysis based on the LCC function developed in the study. Economic efficiencies for optimal seismic upgradings of the continuous PC segmental bridges are assessed using the proposed LCC functions and benefit-cost ratio.

Keywords: life cycle cost effectiveness, economic assessment, seismic upgrading, bridges, damage costs, road user costs

1. Introduction

Bridges are major facilities for modern urban transportation and essential to regional or national economics. Failures or damages of critical bridges may cause indirect losses such as degradation of productivity in regional economic activities and severe difficulties in emergency responses and subsequent recoveries to the earthquake as well as direct losses like physical damages and human losses. Recently, there have been many significant earthquakes such as the 1994 Northridge earthquake in California, USA, and the 1995 Hyogoken-Nanbu earthquake in Japan, etc. These earthquakes gave enormous impacts to awaken the public concern about possible earthquake disasters in Korea as well as in Japan. These events demonstrated the importance of seismic hazard mitigation in the design and upgrading of bridges. Especially in the case of large-scale bridge projects, it may be very important to assure cost-effective design and upgrading of bridges.

Recently, Ang and De Leon (1997) and Ang *et al.* (1997) proposed methodologies for cost-effective seismic design and upgrading of buildings based on the minimum expected life cycle cost (LCC) with socio-economic factors. However, there have been, so far, no methodologies available for cost-effective seismic design and upgrading of bridge structures. It should be noted that their failure consequences with socio-economic impacts are totally different from those of building structures. Therefore, it may be stated that a practical and rational methodology for cost-effective seismic design and upgrading of the bridges with the balance of safety and economy should be developed. The methodology should be based on the evaluation of the expected LCC by formulating quantitative direct and indirect damage costs due to a bridge failure. In this paper, a systematic LCC model for bridges is developed, and its application is focused on the economic efficiency assessment for optimal seismic upgradings of continuous PC segmental bridges in a variety of seismic regions.

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2. Assessment of LCC effectiveness and economic efficiency

Bridge engineers are faced with a variety of decisions when and how existing bridges should be upgraded or retrofitted, and whether upgrading is necessary, efficient and economic. Bridges are usually owned and operated by local or central governments responsible for proper management of a large number of bridges. Obviously there won't be sufficient funds available for upgrading or retrofitting all the bridges operated by a government. Moreover, the priority and optimal decision for upgrading should be ranked or made by evaluating economic efficiency of the alternative upgrading methods. This can be done with the well-known benefit/cost (*B*/*C*) ratio, where the benefit *B* is the reduction in net present expected costs due to the increased safety, which can be obtained by subtracting life cycle damage costs of upgraded bridge from those of existing bridge. The cost *C* should include all the expenditures for upgrading of existing bridge.

For evaluating the LCC effectiveness and economic efficiency, a reasonable LCC model is required. Although Chang and Shinozuka (1996) developed a conceptual framework for LCC analysis for seismic upgrading of bridge system, the approach includes only regional seismic risk regardless of structural types. Accordingly, Chang and Shinozukas framework do not consider damage costs associated with level of structural damage due to an earthquake, and thus can not be applied to a LCC analysis specific to a bridge. As such, this study proposes a systematic approach for reliability-based assessment of LCC effectiveness and economic efficiency for alternative bridge upgrading methods. If LCC for a number of alternative upgrading methods would be evaluated, the proposed model and approach also could give an optimal target safety and optimal upgrading method as well.

3. Formulation of LCC model

In this study, reasonable LCC functions applicable to economic efficiency assessment for upgrading of bridge structures are formulated by extending and modifying the existing LCC functions suggested by Ang and De Leon (1997) and Ang *et al.* (1997) for building structures. The total LCC function for economic efficiency assessment is formulated like the criteria proposed by Ang *et al.* (1997), assuming that life-cycle maintenance costs do not affect decision as follows:

$$E[C_T^L] = C + E[C_D^L] \tag{1a}$$

where $E[C_T^L]$ = total expected LCC in present worth; C = all the costs for upgrading of a bridge; $E[C_D^L]$ = expected life cycle damage cost in present worth, which may be defined as

$$E[C_D^L] = \int_0^L E[C_D] \cdot z \cdot v dt = \lambda \cdot vL \cdot E[C_D] \tag{1b}$$

in which v = annual mean occurrence rate of earthquakes with significant intensties; $z = 1/(1+q)$, in which q = discount rate; vL = expected number of significant earthquakes in the lifetime L; λ = discount factor which can be expressed as $\{1-\exp(-\ln(1+q)L)\}/\ln(1+q)$ and $E[C_D]$ = expected damage costs under a significant earthquake. The expcted damage cost $E[C_D]$ can be evaluted by

$$E[C_D] = \sum_t \int_{y_{\min}}^{y_{\max}} \int_0^\infty C_{Di}(x) f_{X|Y}(x) f_Y(y) dxdy \tag{1c}$$

where X = structural damage level; Y = intensity conditional on the occurrence of an earthquake; $f_{X|Y}(X)$ = probability density function (PDF) of X conditional on $Y = y$; and $f_Y(y)$ PDF of Y at the site; and $C_{Di}(x)$ = cost function of damage cost component i.

The major components of the damage cost above is formulated in terms of four damage cost functions-namely, repair/replacement cost function C_R, human loss and property damage cost function C_H, road user cost function C_U due to traffic delay and detour, and indirect regional economic loss function, C_E, as

$$C_D = \sum_i C_{Di}(d_m) = C_R + C_H + C_U + C_E \tag{2}$$

All the cost items above need to be expressed in terms of Park-Ang median global damage index d_m and damage probabilities P_F. The detailed expressions for each cost item are described in the following sections.

3.1 Repair/replacement cost function

A repair/replacement cost function has been developed based on the damage assessment of real damaged buildings due to significant earthquakes by Ang and De Leon (1997) for building structures in Mexico, and by Ang *et al.* (1997) for frame-wall buildings in Tokyo, Japan. Similarly, a repair/replacement cost function for bridge structures could be developed as regression functions in terms of the Park-Ang median global damage indices obtained from damage assessment and available repair cost data for actually damaged or collapsed bridges under past earthquakes as the following equations (Ang *et al.*, 1997):

$$\text{If } 0 \le d_m < d_0, \text{ then } C_R = \alpha_1 d_m^{\alpha_2} C_I \tag{3a}$$

$$\text{If } d_m \geq d_0, \text{ then } C_R = \alpha\ \alpha_3 C_I \tag{3b}$$

where d_m = Park-Ang median global damage index; α_1, α_2 = regression constants to be evaluated from actual seismic damage data; α_3 = a constant representing the ratio of replacement cost to initial cost; and d_0 = a threshold damage index representing irreparable damage level. C_I = structure costs including existing structure cost (C_{Is}) and upgrading cost (C) of bridge.

In this study, in order to obtain the regression parameters of Eq. (3a), instead of elaborate damage assessment as proposed by Ang *et al.* (1997), an indirect approximate approach is attempted by utilizing the statistical investigations on the bridge damage states and corresponding typical repair cost data obtained from the 1995 Hyogoken-Nanbu earthquake, investigated by Shoji *et al.* (1996). They classified the bridge damage states into four major levels such as As, A, B, and C for typical damages of bridges due to the earthquake: for instance, As indicates the collapse damage level; A, the irreparable severe one; B, the moderate one; and C, the minor one. The damage states are based on the survey and interview data obtained from bridge experts. As such, they investigated the relations between the typical damage levels and corresponding repair costs. Many calibration works (e.g. Stone and Taylor, 1993) on the relations between Park-Ang damage indices and damage levels have been already attempted so that damage levels of the structures can be expressed as linguistic damage levels. Thus in this study, recognizing one-to-one correspondence between the qualitative descriptions of damage levels of Park-Ang damage index and the Shoji and other' (1996) damage levels, the parameters of the repair/replacement cost function is estimated.

3.2 Human loss and property damage cost function

In the case of bridge structures, human losses and property damage costs due to an earthquake depend on the number of vehicles or pedestrians passing over the bridge at the time of the incident. In this study, basically, human loss and property damage cost function C_H in Eq. (2) can be formulated as the sum of the value of fatality and injury including property damage costs based on the approach proposed by Ang *et al.* (1997) as follows:

$$C_H = r_F N_0 V_F + r_J N_0 (0.9 V_J + 0.1 V_F) \tag{4}$$

where r_F, r_J = fatality and injury rate, respectively, which are modeled like the ones proposed by Ang *et al.* (1997); V_F, V_J = value of fatality and injury including property damage costs, respectively; and N_0 = expected number of occupants on a bridge.

The values of fatality and injury losses (V_F and V_J) in Eq. (4) can be evaluated using one of the two approaches, namely, human capital approach and willingness-to-pay approach which have been generally used to evaluate the human losses (Lee, 1996). For bridge structures, the expected number of occupants on a bridge N_0 can be approximately obtained from expected traffic density on a bridge as shown in Eq. (5):

$$N_0 = \left(\sum_i N_{P_i}(V_i/V)\right) N_l k_t l_o \tag{5}$$

where i = index for the type of vehicle, which could be passenger (owner-driven) car, large car, taxi, bus, pickup and large truck including single unit truck, dump truck, and semi-trailer; N_{P_i} = number of occupants in the type of vehicle i; V = daily traffic volumes of bridge route; V_i = average daily traffic volumes for vehicle type i on the bridge route; N_l = number of lanes of the bridge; k_t = traffic density(number of vehicles per km); and l_o = bridge length. The average traffic density k_t is an important parameter in transportation engineering, which has been used to estimate traffic velocity and volume. In this study, a classical and most simple model, so-called the Greenshields model (Son and Sinha, 1997) is used, which is based on the linear relationship between traffic velocity and density, given by $k_t = k_j(1 - v_o/v_f)$, in which, k_j = jam density; v_o = average running speed on the bridge; and v_f = free speed on the bridge.

3.3 Road user cost function

This study focuses on the development of a reasonable road user cost function C_U in Eq. (2) to analyze the LCC of bridges. Since the functional failure of a transportation network may cause great impacts to regional economy, the consequences of a bridge damage or failure due to an earthquake may be not only restricted to physical and human losses but also may include much wider aspects such as so-called road user costs and indirect regional economic losses.

Some reports indicated that the collapses of some critical bridges due to the recent significant earthquakes such as the 1989 Loma Prieta earthquake and the 1994 Northridge earthquake in United States, and the 1995 Hyogo-ken-Nanbu earthquake in Japan, etc. gave enormous impacts to the regional socio-economics in terms of so-called road user costs including time delay cost and vehicle operating cost, rather than direct physical damages such as repair costs and human losses. Especially in the Northridge earthquake, it was reported that the road user cost due to the collapse of the critical four bridges exceeded $1.6million per day except indirect regional economic losses associated with trip elimination, area-wide disruption of shipping, or loss of jobs caused by the earthquake emergency (Wesemann *et al.*, 1996). Thus, it should be noted that the road user costs resulting especially from the collapses of critical bridges in a nation or a regional area may be much more fatal than direct physical losses like human losses and property damage costs.

Time delay costs and vehicle operating costs have been generally considered as major cost items of the road user cost (Wesemann *et al.* , 1996; De Brito and Branco, 1998). Thus, in this study, the road user cost function C_U is formulated as the sum of time delay cost C_{TDC} and vehicle operating cost C_{VOC}(i.e.$C_U = C_{TDC} + C_{VOC}$) (i.e.) in terms of Park-Ang median global damage index. The time delay cost and vehicle operating cost are evaluated, respectively, as follows:

$$C_{TDC} = \left\{ \sum_i n_{p_i} V_i u_{1_i} \right\} \Delta t_d t_R \tag{6}$$

$$C_{VOC} = \left\{ \sum_i V_j (u_{2_j} l_d - u_{3_j} l_o) + \Delta t_d \sum_k (V_k u_{4_k}) \right\} t_R \tag{7}$$

where i = an index for type of vehicles which would be classified into those for business or non-business-namely, owner car for business or non-business, taxi or bus for business or non-business, etc.; j = an index for type of vehicles such as owner car, taxi, truck, bus etc.; k = an index for type of commercial vehicles such as taxi, truck and bus; n_{P_i} = number of passengers in each vehicle type $i \cdot V_i, V_j$ and V_k = daily traffic volume for each different i, j, and k (vehicles/day), respectively; u_{1_i} = average unit value of time per user for each vehicle type i (won/person-hour); u_{2_j} = average unit fuel cost per unit length on the detoured route for each vehicle type j (won/person-hour); and u_{3_j} = average unit fuel cost per unit length on the original route including the bridge for each vehicle type k (won/person-hour); u_{4_k} = average operator wages for each type of vehicle k (won/vehicle-hour); and Δt_d = the additional delay time, which could be obtained as follows:

$$Dt_d = \frac{l_o}{v_o} - \frac{l}{v} \tag{8}$$

where l_o, l = the length(km) of the bridge route(the route including the bridge) or detour routes at pre- and post-earthquake periods, respectively; and v_o, v = the traffic speed on the bridge route or detour routes at pre- and post-earthquake period, respectively.

Although each of Eqs. (6) and (7) is recently developed in the traffic engineering, these formulas could be directly used for effectively evaluating the road user cost. However, there are some important parameters that should be carefully considered in the applications. Since Korea Traffic Development Institute (KOTI) (1992) in Korea extensively researched into unit vehicle operating costs and time delay costs due to traffic congestion based on the human capital approach, this study utilizes these research results so as to develop the cost-effective optimal criteria for bridge structures.

The following assumptions and considerations are made in the modeling of the road user cost function proposed in this study: (1) a bridge damaged due to a significant earthquake would be completely closed and all the traffics would be detoured during inspection or repair/replacement of the bridge for all ranges of Park-Ang median global damage indices, according to the criteria recommended by the KOTI (1992); (2) two different values of time depending upon business or non-business trip as aforementioned are considered; (3) the average time delay is estimated with changes of average velocities for pre- & post-earthquake periods; (4) The additional operator wages of commercial vehicles such as taxi, pickup, bus, and large truck due to time delay are separately included in the vehicle operating costs according to the KOTI(1992) criteria although they may be considered as time delay cost; and (5) in addition, only vehicle fuel costs except oil and maintenance cost of each vehicle are considered since they comprise most of the vehicle operating cost.

3.4 Indirect regional economic loss function

It may not be easy to estimate the indirect regional economic losses in case of bridge structures. According to the research results by Ang *et al.* (1997), indirect regional economic losses (defined as second round losses by Ang *et al.* (1997)) were approximately same as the first round loss (functional damage cost). Moreover, Seskin (1990) reported that the indirect benefit to regional economy due to highway improvement is about 50-150% of the user benefits. Thus, the indirect regional economic losses may be considered as the about same as the road user costs obtained from proposed method in this study. Further researches for the economic impact assessments of major critical bridges in urban area are required for more realistic formulation.

4. Seismic damage and reliability assessment

Extensive assessments of structural damages and reliabilities under various earthquake load intensities are obviously needed to compute the expected LCC. Only reinforced concrete (RC) pier elements of a bridge are usually taken into consideration for the damage and reliability assessment. For damage assessment of a pier element, the well-known Park-Ang damage model is used. In addition, for damage assessment of a bridge system, global damage model is required. The global damage index of the bridge system can be obtained as union of events of local damage indices (Ang *et al.,* 1997).

For the proper assessment of a component damage under random seismic loads, the bridge should be adequately modeled and analyzed in order to obtain its response under simulated or recorded earthquake ground motions. Since structural response under a significant earthquake load may be nonlinear and hysteretic, computation of the response statistics under random earthquake loads using appropriate random structural models and capacities becomes an extremely complex task. Here a Monte Carlo simulation (MCS) is used to compute the desired response statistics. For the purpose, the SMART-DRAIN-2DX (Lee 1996) that has been modified to perform the desired MCS is used, which is an extension of the computer program, DRAIN-2DX. In the program, the critical structural components are modeled using the beam-column element in DRAIN-2DX with a tri-linear elasto-plastic hysteresis. Earthquake ground motions used as input for the simulation can be either actual earthquake records or samples of nonstationary, filtered Gaussian processes with both frequency and amplitude modulation based on the Yeh & Wen model (Lee 1996). In order to reduce computational costs and time, a relatively small number of simulations (200) which gave satisfactory results in previous study (Lee 1996) is also performed with this program, and a joint PDF is fitted to the computed damage response statistics of interest. This joint PDF of the relevant damage response statistics is then used to compute the following damage probabilities.

The exceedance probability of a specified limit state of a RC pier element, i.e., the probability of failure P_{F_i} for the element i can be obtained, using the MCS technique. The threshold values for the specified limit states could be 0.4 for irreparable damage level and 0.8 for collapse level, which were calibrated by Stone and Taylor (1993). Here the events exceeding the irreparable damage level and collapse level are defined as damage limit state and ultimate limit state, respectively.

The life-cycle system failure probability P_F^L can be evaluated as follows:

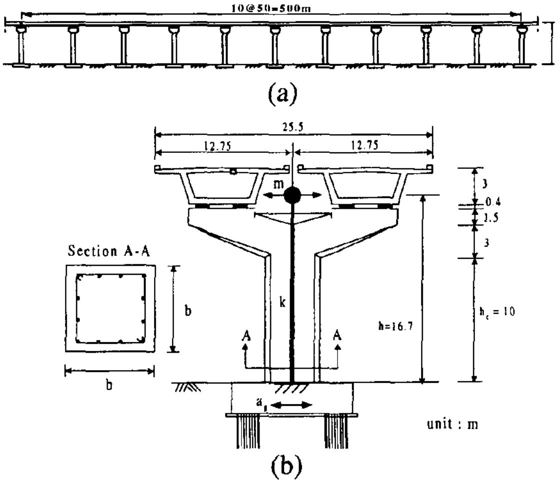
$$P_{F_s}^L = \int_Y P(D>d|Y_L=y)f_{Y_L}(y)dy \qquad (9)$$

where $f_{Y_L}(y)$ is PDF of the earthquake intensity at a given site in the life span L. $P(D>d|Y_L=y)$ represents the conditional failure probability that the structural damage will exceed a specified damage level d, given that an earthquake with an expected maximum ground acceleration y has occurred. The PDF $f_{Y_L}(y)$ can be computed using an available and reasonable seismic hazard curve at a site.

The statistical uncertainties recommended by Lee (1996) are utilized as the statistical uncertainties essential for seismic reliability analysis for this study. The uncertainties with earthquake loads and resistance are modeled as lognormal random variables. Also, a lognormal distribution is chosen for the damage response statistics.

5. Application Example

The proposed method for the economic efficiency assessment for optimal seismic upgrading of bridges based on the expected LCC is applied to continuous PC bridges. The applied model bridges for the study are 10 span continuous PC bridges with 50 m long for each span, which were actually constructed as urban expressways by PSM (Precast Segmental Method) in Seoul as shown in Fig. 1. The bridge was not designed against earthquake since it had been constructed before 1992 when seismic design for bridges were not required by the bridge code in Korea. For a comparative study, it is also assumed that the example bridges are located in Seattle, a moderate seismicity (moderate risk) region, and Boston and Seoul, minor seismicity (minor risk) regions, respectively. Some reasonable seismic hazard curves for the regions are used in the study, but the details are referred to the references (Kramer 1996; Lim 1999).



(a)

(b)

Fig. 1. Model bridge and dynamic response model (a) profile, (b) typical pier section and transverse dynamic response model.

5.1 Seismic upgrading and initial costs

Since only one hinged connection is located at the fourth pier from left side as shown in Fig. 2(a) and all the masses of the superstructure are concentrated on the pier, the existing bridge is very vulnerable to earthquakes. If a bridge do not satisfy seismic design criteria-Standard Specification for Highway Bridges (AASHTO, 1996) in the study, the bridge would be upgraded by an alternative upgrading approach. Table 1 shows the results of upgrading of the bridge. A computer program, PCACOL (Poland Cement Associate, 1999) on the basis of the ACI 318-85 provisions is utilized for the seismic designs for increasing pier section.

The initial costs are estimated based on the cost of actual construction. The construction cost spent for upgrading of the bridge is related to the installation cost of stoppers and cost of increasing pier sections. If the pier capacities with the installation of stoppers do not satisfy the seismic criteria, pier sections are increased. Table 1 shows upgrading costs corresponding to the alternative upgrading method.

5.2 Seismic reliability assessment

An extended SMART-DRAIN-2DX is used as a main tool for the numerical analysis. Since all the piers have same capacities and dimensions, a pier is modeled using an equivalent beam-column element with tri-linear elasto-plastic hysteresis. The dynamic excitation and response of a bridge subjected to an earthquake ground motion in the form of ground acceleration $a_g(t)$ can be best explained by means of a single-degree-of-freedom model of a bridge structure. The simplified model of an equivalent single-column bent can provide a reasonable approximation to the true seismic response of the bridge, as long as the bridge is straight and consists of a large number of equal spans and piers with an equal height or stiffness. Only the transverse response of the bridge under horizontal earthquake ground motion is considered, since the transverse and longitudinal responses of the bridge are virtually identical under the rigid body assumption of the superstructures. In the simplified bridge model, the seismic mass m is lumped at the top of the single-column bent. Since the damping ratio of the fundamental mode for RC structures is generally in the range of 1 to 10 percent, 5% damping ratio is applied in this study.

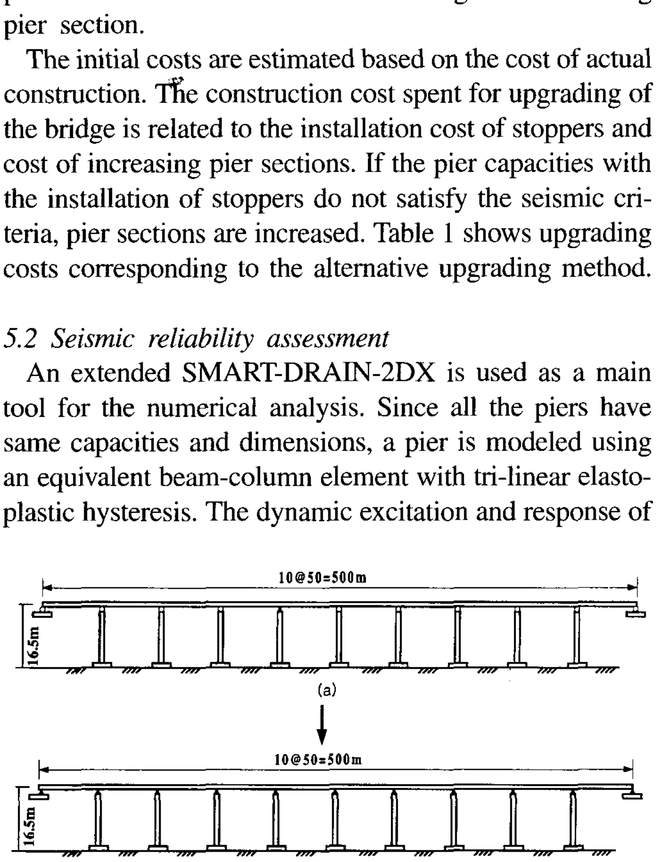


Fig. 2. Existing bridge and upgraded bridge (a) existing bridge (b) upgraded bridge.

Table 1. Upgrading cost (million won).

Seismic region	Seismic risk	Costs of existing bridges	Upgrading costs	Upgrading Method
Seattle	Moderate	1800	110	Stoppers and increase of sections
Boston	Minor	1800	70	Stoppers only
Korea	Minor	898.9	45	Stoppers only

5.3 Repair/replacement cost

As aforementioned, based on the one-to-one correspondence between the qualitative descriptions of damage levels of Park-Ang damage index and Shoji and others' (1997) damage levels as presented in Table 2, the parameters in Eq. (3) are evaluated. As shown in the table, first, Park-Ang median global damage indices are selected as mean values of each range of Park-Ang damage index. Then, the parameters (α_1, α_2) in Eq. (3) are made to be obtained from a nonlinear fitting with three points (0, 0), (0.175, 0.05), and (0.325, 0.2) for Park-Ang median global damage indices and the repair/replacement cost ratios corresponding to each of the damage level. The parameter α_3 in the equation representing ratio of replacement cost to initial cost are obtained as 1.3 by considering demolition costs (30% of initial cost) as shown in Table 2.

Accordingly, the repair/replacement cost function is developed as follows:

$$\text{If } 0 \le d_m < 0.4, \text{ then } C_R = 2.457\, d_m^{2.2346} C_I \tag{10a}$$

$$\text{If } d_m \ge 0.4, \text{ then } C_R = 1.3 C_I \tag{10b}$$

5.4 Human losses and property damage cost

For the evaluation of human losses, traffic conditions should be required. Table 3 shows assumed data related to the traffic flow of the bridge route and detour route. The three different traffic velocities for each route 30, 50 and 70 km/h are considered for the study. In the paper, it is assumed that there is only one detour route available if the bridge route is closed.

The vehicle speed on a detour route at post-earthquake period, which is essential to evaluate human losses and

Table 2. Repair/replacement cost data obtained from relations between Park-Ang damage index and Shoji and other' damage level.

Park-Ang damage index		Shoji and others damage levels and corresponding repair/ replacement costs		$\frac{C_R}{C_I}$
Ranges of Park-Ang DI	d_m	Shoji and others (1997)'s damage level	Repair/Replacement Costs (million yen)	
0.10≤D<0.25(Minor)	0.175	C(Minor)	12.2	0.05
0.25≤D<0.40[1](Moderate)	0.325	B(Moderate)	48.6	0.20
0.40≤δ<0.80[2] (Severe)	>0.40	A(Severe)	331.7	1.30
D>0.80(Collapsed)	>0.80	As(Collapsed)	331.7	1.30

[1], [2] Threshold values representing irreparable damage and collapse level, respectively, recommended by Stone and Taylor (1993).
Initial cost C_I = 252 million yen.

Table 3. Assumed data and traffic data at pre-earthquake.

Route	Design speed (km/h)	Freeflow speed (km/h)		Traffic speed (km/h)		Number of Lanes	Length of Roads (km)
Bridge route	70	80	30	50	70	6	10
Detour route	70	80	30	50	70	4	18

road user cost, can be obtained from the follwing KOTIs criteria (1992) expressed as volume-capacity ratio *V/C*, and vehicle speed v and free-flow speed v_f:

$$v = \frac{v_f}{1+0.91(V/C)^3} \tag{11}$$

where C = daily traffic capacity(*SF/K*), in which *SF* = hourly traffic capacity, and K = 0.1.

The hourly traffic capacity is easily obtained from the formula developed by the KOTI(1992) as follows:

$$SF = 2{,}200 \times N \times f_w \times f_{hw} \times f_i \tag{12}$$

where N = number of lanes; f_w = adjustment factor for narrow width; f_{hv} = adjustment factor for heavy vehicles; f_i = adjustment factor for intersection obstruction. The three adjustment factors are selected as 0.85, 0.71, and 0.90 in the study according to the KOTI(1992) criteria, respectively.

From Eqs. (11) and (12), daily traffic capacities and traffic volumes for the three different vehicle speeds – 30, 50, and 70 km/h – at pre-earthquake can be obtained. Assuming that all the traffic at post-earthquake would use the detour route, vehicle speeds are obtained as shown in Table 4.

As such, the expected number of occupants on a bridge N_o for evaluating human losses in Eq. (5) is evaluated from these data of the traffic volume and speed. In addition, for Seoul, the fatality loss including property damage cost V_F in Eq. (4) are obtained as 3.5 billion won based on the KOTIs research results using human capital approach based on the traffic accident cost data in Seoul. However, for USA 7 million dollars (about 70 billion won) by Lee(1996) are considered as fatality costs, by converting to Korean currency (950/$). The injury losses are considered as 6% of the fatality losses based on the KOTIs statistics. The fatality rate r_F and injury rate r_I are obtained as functions of collapse probabilities based on the model proposed by Ang *et al.* (1997). The basic assumptions for the evaluation of the expected number of occupants on the bridge are as follows: The number of lanes of the bridge route is 6; the total length of the bridge is 500 m; the jam density of 160 vehicle/hr; and the free speed is 80 km/h. Thus, for instance, from the given assumptions and traffic conditions given in Table 4, the human loss and property damage cost for 50 km/h traffic conditions for the example bridge in Seoul can be expressed in terms of the collapse probabilities as follows:

$$\text{If } 0 \le d_m < 0.8, \text{ then } C_H = 4.158 \times 10^{11}[P(D>0.8)]^{1.6} \,(₩) \tag{13a}$$

$$\text{If } d_m \le 0.8, \text{ then } C_H = 1{,}078 \times 10^{11}[P(D>0.8)]^{1.6} \,(₩) \tag{13b}$$

5.5 Road user costs

This study focuses on the road user costs. All the traffics on the bridge route are assumed to detour whenever the bridge experiences a considerable damage due to a sig-

Table 4. Traffic conditions at pre- & post- earthquake periods.

		Bridge route	Detour route	Bridge route	Detour route	Bridge route	Detour route
Pre-earth quake	Vehicle speed (km/h)	30	30	50	50	70	70
	Daily traffic volume	88,000	59,000	62000	42,000	39,000	26,000
Daily traffic capacity		72,000	48,000	72,000	48,000	72,000	48000
Post-earth quake	Vehicle speed (km/h)	–	3.0	–	7.8	–	24.9
	Daily traffic volume	Closed	147,000	Closed	104,000	Closed	65,000

nificant earthquake. As shown in Table 3, a detour route is assumed to have the road length of 18km. The time delay costs and vehicle operating costs due to additional operator wages are evaluated with the average delayed time estimated based on the procedure and assumptions described above. The vehicle operating costs are estimated only in terms of fuel costs with the additional detour length of the traffic volume on the bridge route for the pre-earthquake period and reduced average velocities. The vehicle operating costs of the traffic volumes on the bridge route and detoured routes are obtained with the reduced average velocity for post-earthquake period. Table 4 shows the calculated traffic velocities at pre- & post-earthquake periods for three different traffic conditions in order to evaluate the road user costs. As a result, the following road user costs for Seoul, for example, are obtained in terms of Park-Ang median global damage indices:

If $d_m < 0.07$, then $C_U = 5.63\times10^{10} d_m$ (₩) (14a)

If $0.07 \le d_m < 0.20$, then

$$C_U = (9.526\times10^{10})d_m - 2.702\times10^{9}\ (₩) \quad (14b)$$

If $0.2 \le d_m < 0.40$, then

$$C_U = (2.325\times10^{12})d_m - 4.487\times10^{11}\ (₩) \quad (14c)$$

If $d_m \ge 0.4$, *then* $C_U = 5.326\times10^{12}$ (₩) (14d)

Finally the indirect regional economic losses C_E in Eq. (2) are evaluated by assuming that they are about same as the road user costs.

5.6 Reliability-based LCC effectiveness and economic efficiency assessment

With the SMART-DRAIN-2DX, reliabilities of the bridges for the three seismic regions are obtained for damage limit state and collapse limit state, respectively, as shown in Table 5. Based on the results of these reliabilities, the expected LCCs are shown in Table 6, for the case of the three different regions Seattle, Boston and Seoul.

Table 5. Lifetime failure probability.

Region		Seattle	Boston	Seoul
Existing bridge	Damage	5.44×10^{-2}	6.14×10^{-3}	5.49×10^{-4}
	Collapse	7.31×10^{-3}	6.15×10^{-3}	1.82×10^{-5}
Upgraded bridge	Damage	5.74×10^{-3}	3.42×10^{-4}	7.51×10^{-6}
	Collapse	4.64×10^{-4}	1.52×10^{-5}	7.61×10^{-8}

As shown in Fig. 3(a) and Table 6, in the case of the existing bridge without upgrading, regardless of other parameters, the road user costs and indirect economic losses are 91~99% of the total life cycle damage costs. This indicates that they comprise most of the damage costs of the bridge. As a result, it is found that the road user costs and indirect economic losses are the most governing cost items for the LCC analysis and economic efficiency assessment. On the contrary, since repair/replacement costs and property damage and human losses are less than 10% of the LCC as shown in the table, these costs are negligible compared with the indirect damage costs.

In the case of the upgraded bridge, as shown in Fig. 3(b), the relative ratios of upgrading costs, road user costs and indirect regional economic losses to total LCC for each different region are very sensitive to the variations of the traffic conditions and seismic regions, although road user costs and indirect regional economic losses still comprise most part of the damage costs. Thus it may be easily found that traffic conditions and upgrading costs as well as road user costs and indirect regional economic losses are important but very sensitive parameters for evaluating LCC effectiveness and economic efficiency for seismic upgrading of bridges. Moreover, it may also be seen that the level of seismicity is also one of important factors because it significantly affects the results as shown in Table 6 and Fig. 3(b).

Fig. 4 shows the sensitivity of B/C ratio to the variations of traffic speeds and seismicity. As expected, more eco-

Table 6. LCC effectiveness and economic efficiency assessment for different traffic velocities.

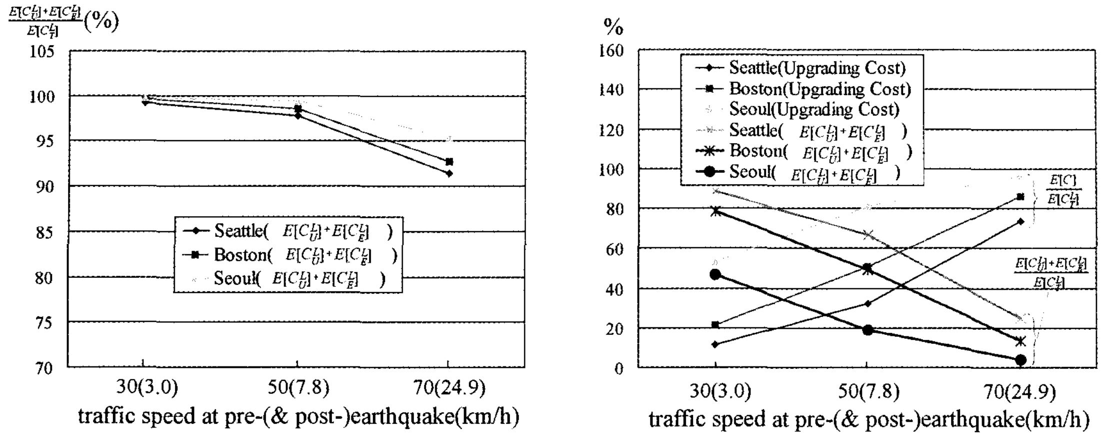
(cost unit : million won, 950won/dollar)

		Seattle			Boston			Korea		
Vehicle speeds of bridge and detour routes at pre-earthquake(km/h)		30	50	70	30	50	70	30	50	70
Vehicle speeds of detour routes at post-earthquake(km/h)		3	7.8	24.9	3	7.8	24.9	3	7.8	24.9
Each expected LCC item of existing bridge (million won)	$E[C_R^L]$	175 (0.2%*)	175 1.0%)	175 (6.3%)	27 (0.3%)	27 (1.1%)	27 (6.7%)	3 (0.2%)	3 (0.8%)	3 (4.6%)
	$E[C_H^L]$	322 (0.5%)	193 (1.2%)	64 (2.3%)	8 (0.0%)	8 (0.0%)	8 (0.0%)	0. (0.0%)	0. (0.0%)	0. (0.0%)
	$E[C_U^L]$	29,900 (49.6%)	7,850 (48.9%)	1,270 (45.7%)	4,410 (49.8%)	1,160 (49.3%)	187 (46.4%)	717 (49.9%)	191 (49.7%)	31 (47.7%)
	$E[C_E^L]$	29,900 (49.6%)	7,850 (48.9%)	1,270 (45.7%)	4,410 (49.8%)	1,160 (49.3%)	187 (46.4%)	717 (49.9%)	191 (49.7%)	31 (47.7%)
	$E[C_D^L]$	60,297 (100%)	16,068 (100%)	2,779 (100%)	8,859 (100%)	2,355 (100%)	403 (100%)	1,437 (100%)	384 (100%)	65 (100%)
	$E[C_T^L]$	60,297 (100%)	16,068 (100%)	2,779 (100%)	8,859 (100%)	2,355 (100%)	403 (100%)	1,437 (100%)	384 (100%)	65 (100%)
Each expected LCC item of upgraded bridge (million won)	Upgrading cost(C)	1,130 (11.3%)	1,130 (32.5%)	1,130 (73.7%)	710 (21.3%)	710 (50.7%)	710 (86.2%)	450 (53.2%)	450 (80.9%)	450 (96.4%)
	$E[C_R^L]$	26 (0.3%)	26 (0.7%)	26 (1.7%)	3 (11.3%)	3 (11.3%)	3 (11.3%)	0. (11.3%)	0. (11.3%)	0. (11.3%)
	$E[C_H^L]$	7 (0.0%)	4 (0.1%)	1 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0. (0.0%)	0. (0.0%)
	$E[C_U^L]$	4,430 (44.3%)	1,160 (33.3%)	188 (12.3%)	1,310 (39.3%)	344 (24.6%)	56 (6.8%)	198 (23.4%)	53 (9.5%)	9 (1.9%)
	$E[C_E^L]$	4,430 (44.3%)	1,160 (33.3%)	188 (12.3%)	1,310 (39.3%)	344 (24.6%)	56 (6.8%)	198 (23.4%)	53 (9.5%)	9 (1.9%)
	$E[C_D^L]$	8,892 (88.9%)	2,350 (67.5%)	403 (26.3%)	2,623 (78.7%)	691 (49.3%)	114 (13.8%)	396 (46.8%)	106 (19.1%)	17 (3.6%)
	$E[C_T^L]$ 1)	10,002 (100%)	3,480 (100%)	1,533 (100%)	3,333 (100%)	1,401 (100%)	824 (100%)	846 (100%)	556 (100%)	467 (100%
Benefit(B)2)		51,404	13,718	2,376	6,236	1,664	289	1,041	278	48
Benefit-cost ratio(B/C)		45.5	12.1	2.1	8.8	2.3	0.4	2.3	0.6	0.1

1) Upgrading cost C+life cycle expected damage cost $E[C_D^L]$ of upgraded bridge.
2) $E[C_D^L]$ of existing bridge-$E[C_D^L]$ of upgraded bridge.
*value in parentheses mean the relative ratios of each cost to the total LCC.

nomic efficiency (B/C = 2.1~45.5 for Seattle; B/C = 0.4~8.8 for Boston; and B/C = 0.1~2.3 for Seoul) is achieved for the region of higher risk. Basically in minor seismic regions, upgrading cost may be one of governing cost items, depending on its ratio to the initial cost and thus ralatively smaller ratios of expected life cycle damage costs to the total LCCs are expected especially under a good traffic flow (for instance, 70/24.9 km/h)(see Fig. 3). In this case, the B/C ratios may become less than 1.0 (when traffic speed for Boston is 70/24.9 km/h and those for Seoul, 50/7.8 and 70/24.9 km/h). Therefore, it may not be always true that all the bridges which do not satisfy seismic criteria should be upgraded especially in the relatively minor seismic regions. Accordingly, it is essential to carefully assess the LCC effectiveness and economic efficiency in minor regions.

In addition, Fig. 5 shows, as an example, the sensitivity of B/C ratios to the variations of traffic speed and upgrad-



(a) without upgrading (b) with upgrading

Fig. 3. Sensitivity of major cost items to the variations of traffic speeds and seismicity.

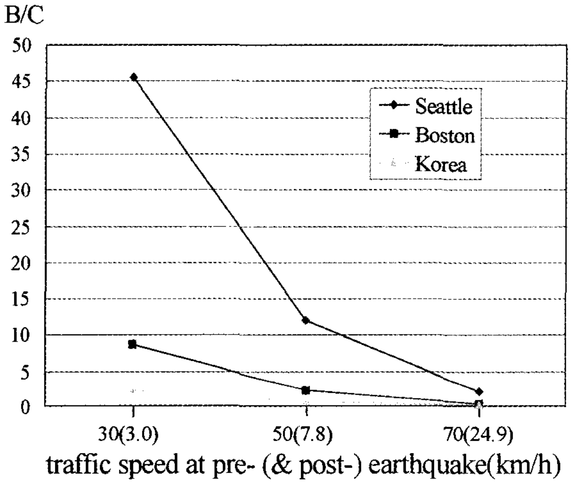


Fig. 4. Sensitivity of B/C to the Variations traffic speeds and seismicity.

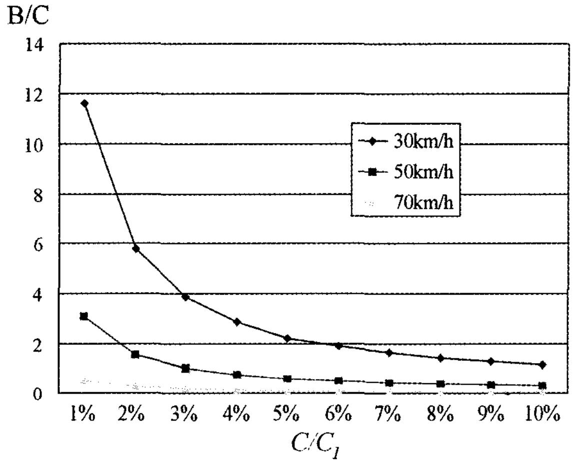


Fig. 5. Sensitivity of B/C to the variations of traffic speed and upgrading cost for Seoul.

ing cost for Seoul. When relative ratios of upgrading costs increase from 1 to 10%, the B/C ratios significantly decrease to some insignificant levels. However, the B/C ratios are relatively less sensitive to the upgrading cost ratios in case of relatively better traffic condtions. As a result, it may be observed that the upgrading cost ratio also become significantly important parameter especially in the regions of traffic congestion.

Since seismic design criteria were established in 1992 in Korea, there still exist many bridges constructed before 1992, which may be vulnerable to earthquakes. It is found that the quantification of the priorities of existing bridges is essential to effectively allocate limited funds for their optimal upgrading. Thus, it may be stated that the approach proposed in the study can be useful for the LCC-based optimal decision and economic efficiency assessment for seismic upgrading of existing bridges.

In this application only one upgrading method is investigated for the three different seismic regions. However, as aforementioned, if LCC effectiveness and economic efficiency for a number of alternative upgrading methods would be assessed, it is not difficult to obtain an optimal target safety for upgrading and optimal upgrading method as well, which could give maximum benefit with minimum upgrading cost.

Based on the observations, it may be summarized that the road user costs and indirect regional economic losses are the most governing cost items in the LCC analysis; the traffic conditions are also important, which could give significant influence on these costs; and finally economic efficiency should be carefully assessed especially in a minor seismic region.

5. Conclusions

This study proposes a systematic procedure for the reliability-based LCC effectiveness and economic efficiency assessment for seismic upgrading of continuous PC bridges. A rational LCC model for bridges is established and successfully expressed in terms of Park-Ang median global damage indices and damage probabilities. The proposed approach is successfully applied to model bridges of a variety of seismicity regions.

It is found that road user costs and indirect regional economic losses must be considered as the most important parameters in the LCC analysis for bridge structures. It may be firmly stated that the quantification of the priorities of existing bridges based on the LCC analysis is essential to effectively allocate limited funds for optimal upgrading of seismically vulnerable bridges especially in moderate or minor seismicity regions. Thus, it may be concluded that the approach proposed in the study can be useful in practice for the LCC-based optimal decision and economic efficiency assessment for seismic upgrading of existing bridges.

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