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SEISMIC RETROFIT PRIORITIZATION OF BRIDGES BASED ON DAMAGE RISK AND FAILURE COST ANALYSIS

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SUMMARY

A methodology based on seismic damage risk and failure cost analysis is developed for seismic retrofit prioritization of bridges. To evaluate the seismic damage risk of bridges properly, a probabilistic analysis is required. A corresponding simulation procedure is first developed by using a simplified bridge model. This bridge model includes the damage states of various vulnerable components as well as various phenomena involved in the realistic seismic behaviors of girder-type bridges. In addition, to reflect the relative effect and importance of vulnerable components and bridge systems, weighting factors are utilized. The weighting factors are determined by using the failure cost of structural components and bridges. The ranking indices of bridges are evaluated using the overall damage risk and weighting factors. At the final stage, the vulnerable components in need of seismic retrofit are selected accordingly. The validity of the developed methodology is shown in comparison with the results of the existing methodology in current practice. The retrofit priority of selected model bridges is examined using the developed methodology. The ranking indices of the model bridges retrofitted according to the retrofit priority are also revaluated. From the results, the developed methodology is found to be effectively used in evaluating the retrofit priority of the existing and retrofitted bridges as well as in analyzing the retrofitting effects of the existing bridges.

INTRODUCTION

Many bridges designed prior to the adoption of practical seismic design standards still exist without any aseismic retrofit measures. These bridges need to be retrofitted in some degree. However, it is practically impossible and undesirable to bring all the bridges up to the modern standards to minimize the seismic damage risk. To ensure seismic safety considering limited financial resources the priority of bridges for seismic retrofit should be determined in advance, particularly in the regions of weak and moderate seismic excitations.

Many methodologies have been studied and proposed to establish policies for more efficient seismic retrofits[1~5]. These methodologies rank bridges according to many factors correlated with the damage risk and the corresponding socio-economic effects. Three major variables are considered in these

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methodologies: the seismicity, the vulnerability, and the importance of the bridge. The seismic vulnerability of a bridge among the three major variables is determined using indices based on the simple recognition of unfavorable structural features known to have inadequate performance from the past earthquakes [6]. In these methodologies, bridges sharing certain unfavorable structural features would also share the similar ranking, independent of variations in geometry and other structural properties. Because the geometry and other structural properties could affect the ranking of the bridges, these effects should be included in the ranking decision.

To rank the seismically deficient bridges, therefore, the possibility of partial damage or collapse due to the seismic responses under probable seismic excitations should be examined with both the physical and the socio-economic state of each bridge. However, it is hardly possible to predict the typical ground motions for the probable peak ground accelerations in countries lacking ground acceleration records. On the other hand, it is more practical to analyze the damage risk of a bridge under ground motions using a probabilistic approach. Probabilistic analysis requires a huge amount of calculations. Hence, it is essential to develop an analysis procedure capable of carrying out rapid but yet refined seismic evaluation of bridges for the probabilistic analysis. Using this analysis procedure, a quantitative methodology for determining the retrofit priority considering the probability of seismic damage and socio-economic impacts can then be utilized.

In this study, a methodology based on seismic damage risk and failure cost analysis is proposed to determine the priority of bridges in need of seismic retrofit. Developed first is an advanced simulation method based on a simplified mechanical bridge model, which can examine the damage states of various seismic vulnerable components. This bridge model also includes many important phenomena found in the real bridges under seismic excitations. For convenience, the damage states of vulnerable components are quantitatively evaluated in terms of damage index. The damage risk of vulnerable components can be calculated from the probabilistic distribution of the damage index obtained from seismic analysis and the damage index for predefined failure limit state. To estimate the overall damage risk of bridges from the damage risk of vulnerable components, the relative effect of each vulnerable component should be considered. In addition, to determine the ranking indices of bridges using the overall damage risk, the relative importance among the considered bridges should be considered. Weighting factors are proposed by which the relative impact or importance can be assigned. The weighting factors of vulnerable components and bridges are calculated using the failure cost related directly to the damage. Accordingly, the retrofit priority of bridges is determined from the ranking indices which are evaluated from the overall damage risk and weighting factors of bridges.

A METHODOLOGY BASED ON SEISMIC DAMAGE RISK AND FAILURE COST ANALYSIS

For more practical prioritization of bridges, it may be essential to predict the damage possibility under probable seismic excitations and to reflect the socioeconomic impact due to the failure of bridges. Bridges have various vulnerable components, which can be damaged under seismic excitations. The damage types and levels of these vulnerable components vary according to input excitations and dynamic characteristics of bridges. For the convenience of analysis, it is necessary to quantify the damage state of vulnerable components and the relative importance of vulnerable components or bridges to each other numerically.

In the proposed methodology, damage indices and weighting factors are used. The damage index of each vulnerable component is evaluated by using the simplified mechanical bridge model. This bridge model can consider the damage states of various seismic vulnerable components as well as the other major phenomena. The damage probability P_{ik} of each component is calculated from the probabilistic distribution of the evaluated damage index and the damage index of given failure limit state.

$$P_{ik} = \max_j \left\{ P\left[\frac{(DI_{ik})_j}{(DI_c)_{ik}} > 1 \right] \right\} \tag{1}$$

where i is an index for each structural vulnerable component; j is the total number of each structural vulnerable component in a bridge; k is an index for each bridge; $(Di_{ik})_j$ is the damage index evaluated in accordance with the seismic hazard at a bridge site; and DI_c is the damage index for a predefined failure limit state.

The weighting factors are determined using the cost due to the failure of each structural component or bridge. Provided that the total cost caused by failure of the component i of the bridge k is $(C_F)_{ik}$, and provided that the total cost due to the failure of the bridge k is $(C_F)_k$, the weighting factors of vulnerable components and bridges can be calculated as follows:

$$\lambda_{ik} = \frac{(C_F)_{ik}}{(C_F)_k} \tag{2}$$

$$\lambda_k = \frac{(C_F)_k}{(C_F)_{k,specified}} \tag{3}$$

where λ_{ik} is the weighting factor for the component i of the bridge k; λ_k is the weighting factor of the bridge k; and $(C_F)_{k,specified}$ is the total failure cost of the specified bridge among considered bridges.

Therefore, the overall damage probability P_k of the bridge k is defined as the sum of the equivalent damage probability for predefined failure limit states. Here, the equivalent damage probability $(P_{ik})_E$ is calculated as the product of the damage probability and the weighting factor of each component.

$$P_k = \sum_i (P_{ik})_E = \sum_i (P_{ik} \times \lambda_{ik}) \tag{4}$$

In the same manner, the ranking index is determined by using the overall damage probabilities and the weighting factors for each bridge as follows:

$$RI_k = P_k \times \lambda_k \tag{5}$$

Accordingly, the seismic retrofit priority of bridges can be determined by the ranking indices.

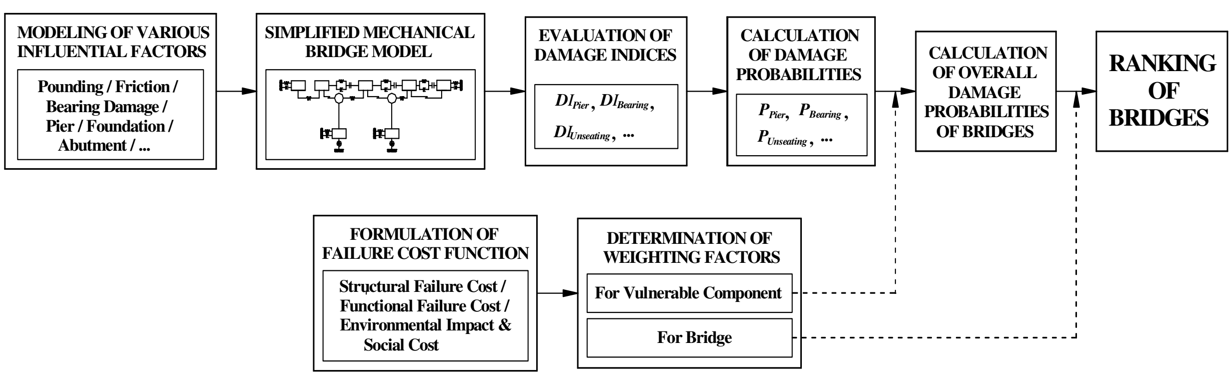


Fig. 1 Conceptual procedure of the developed methodology

FORMULATION OF FAILURE COST FUNCTION

In the proposed methodology, the weighting factors of vulnerable components and bridges are utilized to consider the relative effects of the damage of each component on the damage of the whole bridge or to regard relative importance among the considered bridges. The weighting factors can be determined by using the indicator, which is directly related to the damage level of vulnerable components or bridges such as failure cost. The failure cost has been developed and utilized in the field of economic analysis associated mainly with plan, design, maintenance, and repair/retrofit of structures.

The failure cost is the cost associated with partial or total damage of a bridge to fully comply with its design function. Therefore, the failure cost in this methodology may be defined as the total loss caused by the collapse of a vulnerable component or a bridge due to earthquakes as shown in Figure 2.

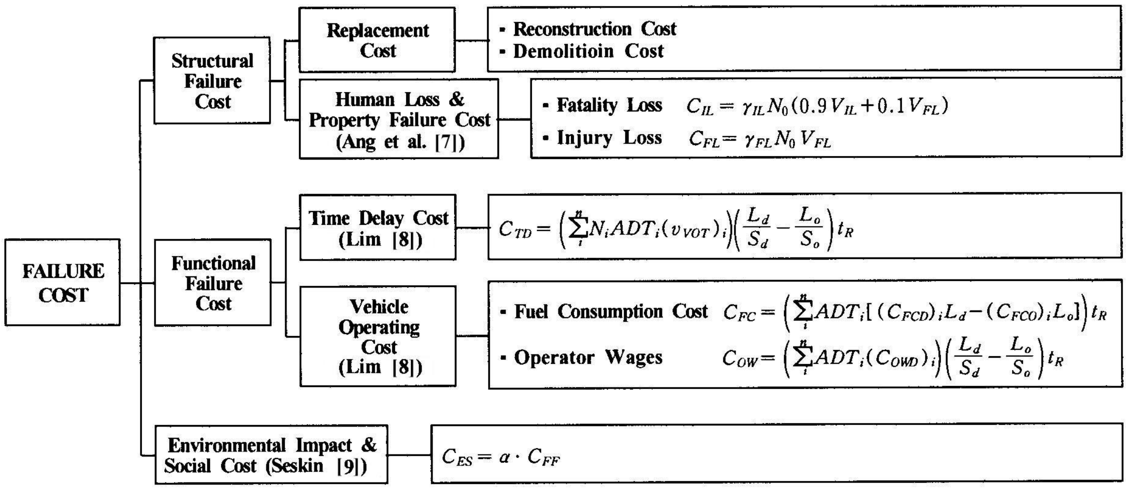


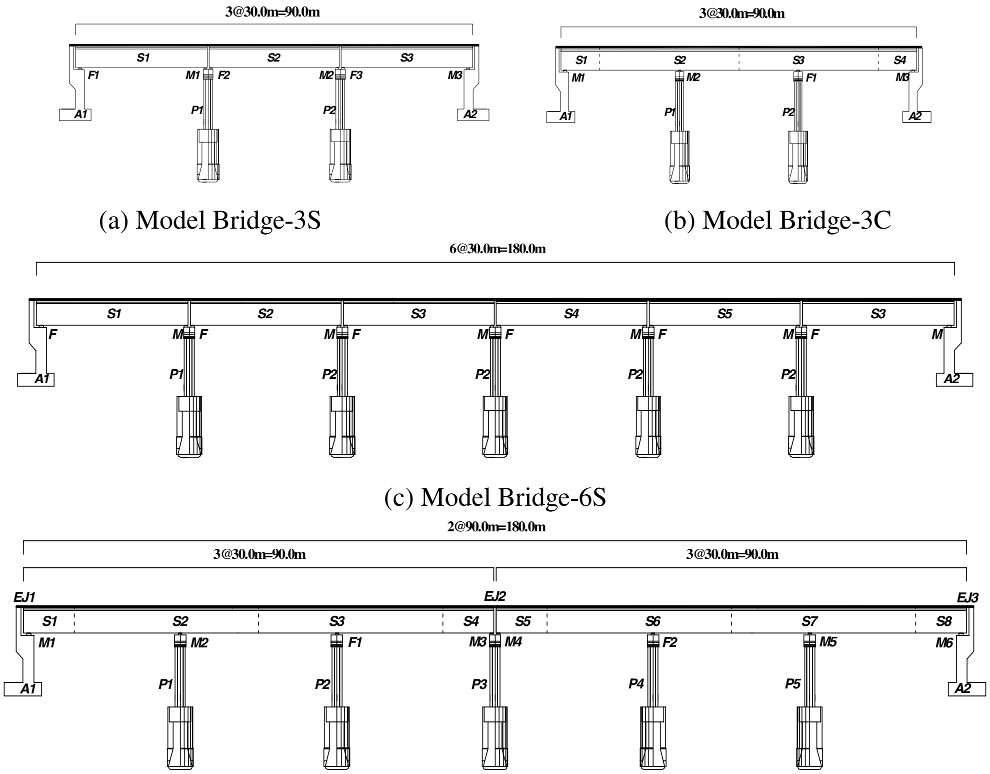
Fig. 2 Failure cost of a bridge due to damage

In Figure 2, r_{FL} is the fatality rate, i.e., the number of death divided by the number of occupants on the bridge, N_o is the number of occupants on the bridge, V_{FL} is the value of fatality, and r_{IL} and V_{IL} are the injury rate and the cost of injury, respectively. i is the index of the vehicle type according to the trip purpose, N_i is the average number of passengers per vehicle type i, ADT_i is the daily traffic volume of vehicle type i expected to cross the bridge (number of vehicles/day), $(v_{VOT})_i$ is the average unit value of time per a passenger on the vehicle type i, L_d is the length of the detour route, S_d is the average traffic speed on the detour route, L_o is the length of the original route, S_o is the average traffic speed on the original route, and t_R is the restoration time to recover the bridge from damaged or collapsed status due to an earthquake. $(C_{FCD})_i$ and $(C_{FCO})_i$ are the average fuel consumption cost per unit length on the detour route and the original route, respectively. $(C_{OWD})_i$ is the average unit wage of the operator for each type of vehicles. α is the constant representing a ratio of environmental impact and social cost to functional failure cost. C_{FF} is the functional failure cost.

BRIDGE MODEL

Bridge considered

Four model bridges are considered in the evaluation of retrofit priority through the proposed methodology. The four model bridges are a 3-span simply supported bridge (Model Bridge-3S), a 6-span simply supported bridge (Model Bridge-6S), a 3-span continuous bridge (Model Bridge-3C), and a 6-span bridge with two 3-span continuous bridges (Model Bridge-6C). The type of four model bridges is the precast prestressed concrete girder bridge. The elevation views of these bridges are shown in Figure 3. The span length of each bridge is equal to be 30m and four bridges are assumed to have the same dimensions for the cross sections of the superstructure and the substructure as shown in Figure 4. The superstructure has cast-in-place concrete deck and diaphragms. Piers are concrete frame with circular columns (D=1.95m, H=12m) on individual deep large diameter caisson (D=4.8m, H=10m) footings embedded in weathering rocks. Seat-type abutments (L=2.9m, W=17m, and H=6.5m) are also used.



(a) Model Bridge-3S (b) Model Bridge-3C

(c) Model Bridge-6S

(d) Model Bridge-6C

Fig. 3 Elevation view of the considered bridges

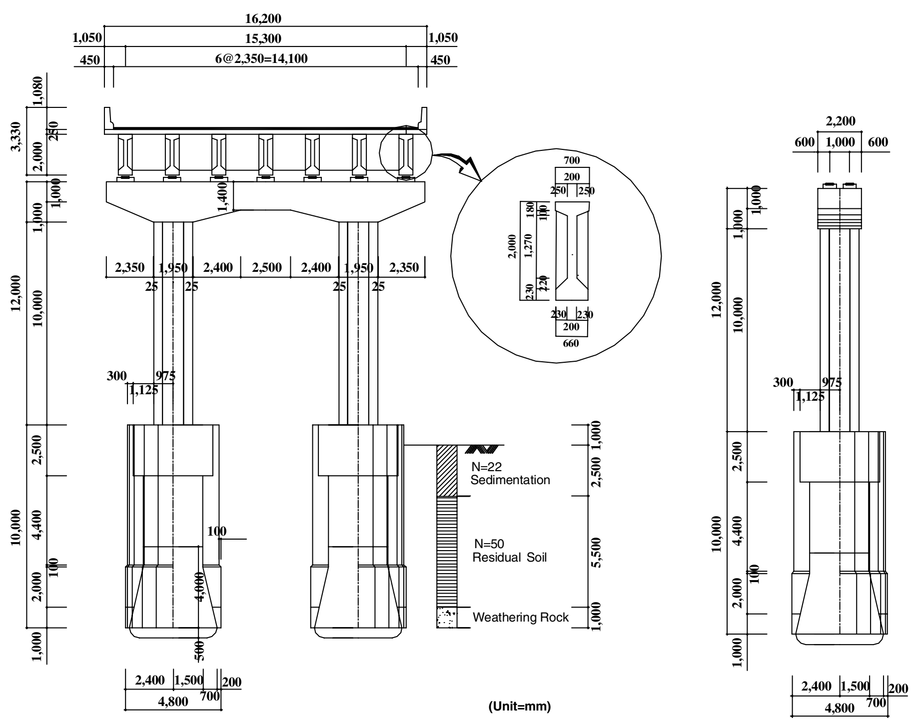


Fig. 4 Cross section of the considered bridges

Damage model of seismic vulnerable components

Bridges have various vulnerable components, which can be damaged under seismic excitations. The damage type and level of these vulnerable components diverse according to input excitations and dynamic characteristics of bridges. The structural components vulnerable to damage in girder-type bridges are the pier, bearing, foundation, and abutment. In addition, there is unseating failure as one of the major causes of bridge collapse. According to the reports from recent strong earthquakes [10~12], it is found that typical failure types are the failure of piers and bearings and unseating failure. In this study, the RC pier, bearing, and unseating are selected as the vulnerable components in girder-type bridges accordingly. The damage index of each vulnerable component is defined as a function of demand to capacity. The damage index is used as only means to quantify the damage state of each component numerically. The damage or failure models of vulnerable components are concisely described in Table 1.

Table 1 Damage model of vulnerable components

Components	Definition	Damage index
RC pier	A linear combination of the damage caused by excessive deformation and contributed by repeated cyclic loading effect (Park and Ang [13])	$DI_{pier} = \dfrac{d_m}{d_u} + \dfrac{\beta}{Q_y d_u} \int dE_h$
Bearing	A function of bearing demand in terms of force or displacement to ultimate capacity of the bearing	$DI_{bearing}^{F} = \dfrac{F_h}{R_{nc}}$, $DI_{bearing}^{M} = \dfrac{d_{mrd} - d_a^M}{d_u^M - d_a^M}$
Unseating	The product of the ratio of maximum response to the minimum supporting length and damage index of the bearing	$DI_{unseating} = \left(\dfrac{d_{mrd}}{N}\right) \cdot DI_{bearing}$

In Table 1, d_m is the maximum response displacement under an earthquake; d_u is the ultimate displacement capacity under monotonic loading; β is the strength deterioration parameter; Q_y is the static yield strength; and dE_h is the incremental dissipated hysteretic energy. F_h is the maximum horizontal force applied to fixed bearing under an earthquake; R_{nc} is the resistance capacity (ultimate strength) of fixed bearing; d_{mrd} is the maximum relative distances; d_a^M is the allowable design displacement; d_u^M is the allowable maximum displacement in the constrained-sliding pot bearing; and N is the minimum supporting length.

Simplified mechanical model of bridges

The analytical model of the 3-span simply supported bridge is represented in Figure 5. This mechanical model is simplified and idealized by using the lumped mass system to perform the analysis more efficiently [14]. In the figure, m, K, and C are the mass, stiffness and damping constant of each element; u_i is the relative displacement to ground; and $\ddot{u}_g$ is the ground acceleration.

The influential factors included in the mechanical bridge model are pounding, friction at the movable supports, effects of bearing damage, abutment stiffness degradation, nonlinear behaviors of R/C piers, and foundation motions. The pounding, which is an interaction between adjacent vibration units, is described by placing spring-damper elements (impact elements) between the masses as shown in Figure 5 and is occurred only when the masses are contacted. The gap distance d_p at the expansion joints can be calculated by considering the expected displacements due to the temperature change, drying shrinkage, creep effect and deflection of the girder. The stiffness S_p of impact element is determined by limited sensitive analysis to the relative distance between adjacent colliding masses. The damping constant C_p can be obtained from the colliding masses, the stiffness of impact element, and the damping ratio of a system [15].

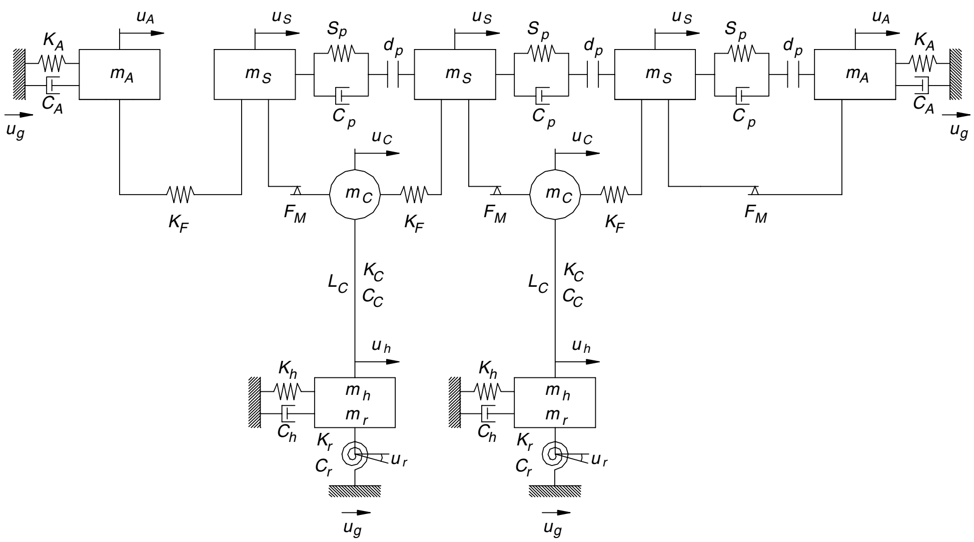


Fig. 5 Idealized mechanical bridge model

The friction between the superstructures and the supports is modeled by the simplified friction element [16]. Before bearings are damaged, the fixed bearing is modeled as a spring element with infinite stiffness K_F, and the movable bearing is modeled as a friction element. After bearings are damaged, both bearings are modeled as friction elements. The friction force F_M comes from the relative motions between superstructure and substructure and is computed by velocity model that is assumed to be proportional to the gravity force at the bearing. The direction of friction forces is decided by relative velocity between the contact units.

To consider nonlinear behaviors of the R/C pier, the material and geometric nonlinearities of the R/C pier are included in the bridge model [14]. The material nonlinearity of the R/C pier is described by adopting the hysteretic model. The geometric nonlinearity is considered by using the $P-\Delta$ effect. The deep foundation is modeled with translational and rotational springs and dampers in order to consider ground conditions as shown in Figure 5. The stiffness (K_h, K_r) and the damping constants (C_h, C_r) of embedded deep foundations in this study are calculated by using the equations proposed by Gazetas [17]. The damping constant given by the Gazetas' formula is for the radiation damping only. Therefore, the total damping constant can be approximated as the sum of the radiation damping constant and material damping constant. The abutment-backfill system is modeled in this study as a one-degree-of-freedom system with nonlinear spring and damper to consider the abutment stiffness degradation as shown in Figure 5 [18]. The longitudinal displacement u_A of the abutment is the total displacement defined as the sum of translational movement and the longitudinal movement due to the rotation of the abutment. The nonlinear spring stiffness K_A can be obtained by using the formulation suggested by Siddharthan et al. [19]. The damping constant C_A for the abutment-backfill system can be obtained from the sum of the radiation damping constant and material damping constant as the similar manner applied to the damping constant of the foundation. A few results are currently available for the damping ratio of the abutment. Wilson and Tan [20] presented that the total damping ratio ranges 25% to 45% through the comparison of time history responses of a finite element model with measured earthquake response of the abutment. This result for the damping ratio can be used in this study.

The governing equations of motion of the simplified mechanical model shown in Figure 5 can be derived from the Lagrange equation [21].

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{u}_i}\right)-\frac{\partial T}{\partial u_i}+\frac{\partial U}{\partial u_i}+\frac{\partial W_d}{\partial u_i}=\frac{\partial W_e}{\partial u_i} \tag{12}$$

where T, U, W_d, and W_e are the total kinetic energy, the total potential energy, work due to the damping forces, and work due to the external forces in terms of a set of generalized coordinates, $u_1, u_2, \ldots, u_n$.

RESULTS AND OBSERVATIONS

The priority of the model bridges for seismic retrofit is evaluated by using the developed methodology. In addition, to verify the validity of the proposed methodology, the ranking index due to the existing methodology used in Korea is estimated. Finally, the ranking indices and seismic retrofit priority for the model bridges retrofitted based on simulation results are revaluated.

The damage probabilities of vulnerable components during the bridge service life are estimated based on the failure limit states and the probabilistic characteristics of damage indices. In this study, the seismic vulnerable components are limited as the R/C pier, bearing, and unseating. Abutments located at both ends of the bridge structures and the pier foundations are assumed to be not damaged. Failure limit states for of both irreparable damage condition and the failure condition are assumed in terms of a damage index. The damage indices for the failure limit states of RC piers are set at 0.40 for the irreparable damage condition and 0.8 for the failure condition, based on the study of Ang *et al.* [22]. For the unseating failure, failure limit states may be obtained from the geometric condition of each model bridge. In this study, the damage indices of unseating are set at 0.75 for irreparable damage condition and 0.85 for the failure condition.

For more realistic evaluation, the properties applied to the analytical bridge model are given below. The pounding stiffness is assumed to be 750 times larger than the elastic stiffness of the pier based on a limited sensitivity study to the relative distance between adjacent colliding masses. A damping ratio ξ_i=0.05 is assumed for the applications. The gap distance between adjacent vibrating units is selected as 6cm for the simply supported bridge and 8cm for the continuous bridge. The friction coefficient of the undamaged fixed bearings is assumed to be 0.03 considering the effect of bearing pressure in the friction surface. However, the friction coefficient of the damaged fixed and movable bearing is assumed as 0.5 based on the previous experimental studies [16]. The basic properties applied for nonlinearity of R/C piers, foundation model, and abutment model are tabulated in Table 2.

Table 2 Parameter values for analytical bridge model

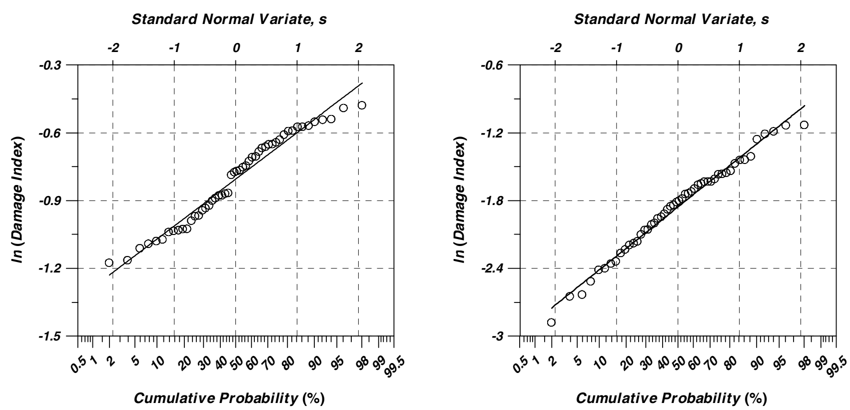
Model parameter	Parameter Value	Model parameter	Parameter Value
Hysteresis model of R/C pier		**Damage model of R/C pier**	
Elastic stiffness	3.573×10^4 *kgf /cm*	(For simply supported bridge)	
Yielding displacement	7.060 *cm*	Ultimate displacement	28.18 *cm*
Yielding force	2.523×10^5 *kgf*	Strength deterioration parameter	0.05832
Post-yielding stiffness	413.4 *kgf /cm*	(For continuous bridge)	
		Ultimate displacement	27.28 *cm*
Foundation model		Strength deterioration parameter	0.06218
Translational stiffness	1.340×10^6 *kgf /cm*		
Translational damping constant	72.45×10^3 *kgf· s /cm*	**Abutment model**	
Rotational stiffness	1.928×10^{12} *kgf· cm*	Translational abutment stiffness	8.157×10^6 *kgf /cm*
Rotational damping constant	28.89×10^9 *kgf· s /cm*		

As the input excitations on the ground surface, artificial seismic excitations are used with various peak ground accelerations. Artificial seismic excitations are simulated by using the well-known SIMQKE code [23], which are forced to be compatible with the design response spectra defined in the Korean Design Codes for Highway Bridges [24].

Seismic retrofit priority of bridges due to the proposed methodology

The priority of model bridges for seismic retrofit due to the proposed methodology is estimated in this section. The model bridges are assumed to be located at the same route of any region. Thus, the seismicity and the social and economic circumstances are regarded to be equal for all model bridges.

Based on the simulation results, the probabilistic distribution of damage indices is obtained as shown in Fig. 8. The figures show the good fit for the log-normal distribution. Therefore, the damage probability for each structural component can be calculated based on the damage index for both failure limit states and the probabilistic distribution of evaluated damage indices. The ranking indices for the model bridges are summarized in Table 3 and 4 for both failure limit states. From the results in the irreparable damage condition, the damage possibility of RC pier is found to be much higher than the occurrence probability of unseating failure in all model bridges. In the failure condition, however, the occurrence probability of unseating failure of the simply supported bridge is found to be slightly high. This result can be attributed to the difference between damage indices applied to both failure limit states. In addition, the RC pier of the Model Bridge-6C is found to be the vulnerable component with the highest damage possibility in the irreparable damage condition. The occurrence possibility of unseating failure is much lower than that of the failure of RC pier. Therefore, the damage risk of the model bridge for irreparable damage condition is expected to be governed by the damage probability of RC piers.



(a) R/C pier (b) Unseating

Fig. 8 Damage indices plotted on the log-normal probability paper

Table 3 Ranking indices for model bridges (Failure limit state: irrepairable damage condition)

Item	Model Bridge-3S		Model Bridge-3C		Model Bridge-6S		Model Bridge-6C	
	RC pier	Unseating	RC pier	Unseating	RC pier	Unseating	RC pier	Unseating
Damage probability (%)	1.45	0.02	7.74	0.00	3.01	0.15	22.59	0.47
Weighting factor for each component	0.736	0.327	0.760	0.328	0.447	0.199	0.437	0.204
Equivalent damage probability	1.07	0.01	5.88	0.00	1.35	0.03	9.87	0.09
Overall damage probability	1.08		5.88		1.38		9.96	
Weighting factor for each bridge	1.000		1.096		1.646		1.757	
Ranking index of each bridge	1.08		6.45		2.26		17.51	

Table 4 Ranking indices for model bridges (Failure limit state: failure condition)

Item	Model Bridge-3S		Model Bridge-3C		Model Bridge-6S		Model Bridge-6C	
	RC pier	Unseating	RC pier	Unseating	RC pier	Unseating	RC pier	Unseating
Damage probability (%)	0.01	0.02	0.04	0.00	0.06	0.12	4.56	0.23
Weighting factor for each component	0.736	0.327	0.760	0.328	0.447	0.199	0.437	0.204
Equivalent damage probability	0.007	0.005	0.03	0.00	0.03	0.02	1.99	0.05
Overall damage probability	0.012		0.03		0.05		2.04	
Weighting factor for each bridge	1.000		1.096		1.646		1.757	
Ranking index of each bridge	0.012		0.03		0.09		3.58	

In terms of the possibility of failure, the RC piers of the Model Bridge-6C rank first, followed by the unseating failure of the Model Bridge-6C. The occurrence possibility is much lower, however. From the results for ranking indices of model bridges, the seismic retrofit priority of model bridges is found to vary in both failure limit states: the irreparable damage condition and the failure condition. This result is derived from the difference between damage indices applied to both failure limit states. The ranking of the model bridges in the irreparable damage condition is as follows: $RI_{Model\ Bridge\text{-}6C} > RI_{Model\ Bridge\text{-}3C} > RI_{Model\ Bridge\text{-}6S} > RI_{Model\ Bridge\text{-}3S}$. The ranking of the model bridges in the failure condition is given below: $RI_{Model\ Bridge\text{-}6C} > RI_{Model\ Bridge\text{-}6S} > RI_{Model\ Bridge\text{-}3C} > RI_{Model\ Bridge\text{-}3S}$.

Verification by comparison with existing methodology

To verify the validity of the developed methodology, the results for the irrepairable damage condition are compared with those using the existing methodology [25]. In comparing the simulation results, the ranking indices calculated without considering pounding and bearing damage based on the current seismic design process are prepared using the developed methodology. The seismicity of all model bridges is assumed to be equal. The social and economic conditions in the bridge site are also considered the same for all model bridges. Table 5 lists the ranking due to both methodologies. In Table 5, the magnitude of ranking indices in each methodology is not same in scales and then cannot be directly compared. Based on the seismic retrofit priority of model bridges, it is found that results using the developed methodology show trends similar to the results using the existing methodology. For one, the ranking indices of continuous bridges or those of simply supported bridges are found to be similar to each other. Likewise, the ranking of continuous bridges is found to be much higher than that of simply supported bridges. Such similar trends prove the validity of the developed methodology.

However, the ranking indices due to proposed methodology in Table 5 are somewhat different from those of Table 3, because the influential factors considered in the developed methodology are different to each other. To verify the effects of various influential factors on the retrofit priority of bridges, the ranking indices of model bridges considering various influential factors are examined and summarized in Table 6. In case IV, the Model Bridge-6C has a priority over the Model Bridge-3C because the relative motions of the RC pier in the Model Bridge-3C are restricted by the pounding between the abutment and adjacent superstructure. Although the detailed results related to the effects of various influential factors on the seismic responses of bridges are not presented herein, related papers are published [14, 16]. Therefore, the developed methodology may give more realistic results in estimating the priority of bridges for seismic retrofit.

Table 5 Ranking due to both methodologies

Methodology	Priority (Ranking index)			
	Model Bridge-3S	Model Bridge-3C	Model Bridge-6S	Model Bridge-6C
Existing methodology	3 (1.24)	+1 (1.39)	3 (1.24)	1 (1.39)
Proposed methodology	4 (2.96)	2 (18.04)	3 (7.60)	1 (33.53)

Table 6 Ranking indices according to effects of various influential factors

CASE	Ranking index (Priority)			
	Model Bridge-3S	Model Bridge-3C	Model Bridge-6S	Model Bridge-6C
a) CASE I	2.62 (3)	17.66 (1)	2.62 (3)	16.38 (2)
b) CASE II	1.71 (4)	17.68 (1)	2.22 (3)	16.38 (2)
c) CASE III	1.62 (4)	20.37 (1)	2.26 (3)	18.95 (2)
d) CASE IV	1.08 (4)	6.45 (2)	2.26 (3)	17.51 (1)

a) Case without considering pounding, friction, and bearing damage
b) Case without considering pounding and bearing damage
c) Case without considering pounding
d) Case with considering pounding, friction, and bearing damage

Effective Retrofit Measures Based on the Ranking of Existing and Retrofitted Bridges

To examine the effects of the retrofit measures on the performance improvement of bridges, the ranking indices of the existing and retrofitted model bridges are estimated for the irreparable damage condition. The retrofit methods adopted in this study are the method applying steel jackets for the RC pier and the method using cable restrainers for unseating failure.

In retrofitting the existing RC pier, 12mm-thick steel jacket is chosen. The steel jacket is assumed to be wrapped around the round-shape pier and perfectly bonded to the pier surface. Effective confining stress of the concrete core due to the steel jacket is obtained from the equilibrium condition of the section. The contribution from the existing hoops to the confinement of the concrete core is excluded.

Cable restrainers ($7\phi12.7$) are assumed to have six 5m-long cables at an expansion joint. The clearance length of the cable restrainer is 10cm. To prevent the superstructure from falling down, the seismic design force of the cable restrainer is assumed to be 1.5 times the reaction due to the dead weight of the superstructure. By applying the minimum elongation to cable fracture as 3.5% as specified in the Korean Design Codes for Highway Bridges [24], the fracture displacement of the cable restrainer is determined to be 17.5cm.

Table 6 summarizes the ranking indices for existing and retrofitted model bridges. Compared to the ranking indices of the existing bridges, the ranking indices of the model bridges retrofitted by steel jackets are found to be small. However, the ranking indices of the model bridges retrofitted by cable restrainers are observed to be slightly large except the ranking index of the Model Bridge-3S. In particular, the ranking index of the Model Bridge-3C is significantly large despite the application of cable restrainers. Based on the simulated results for existing and retrofitted bridges, the application of steel jackets is found to be a positive solution to reduce the seismic damage risk of bridges. However, the installation of cable restrainers can be negative, because the restraining effect of the relative motions due to cable restrainer increases the damage probability of the RC pier. Therefore, the application of cable restrainers as a retrofit measure should be carefully selected based on the results of detailed seismic analysis of bridges. Consequently, the proposed methodology in this study is found to be very effective in evaluation of the retrofit priority of bridges as well as in the analysis of retrofitting effects.

Table 7 Ranking indices for existing and retrofitted bridges

	Model Bridge-3S	Model Bridge-3C	Model Bridge-6S	Model Bridge-6C
Existing bridges	1.08	6.45	2.26	17.51
Bridges retrofitted by steel jacket	0.01	0.00	0.13	0.73
Bridges retrofitted by restrainer	0.93	9.27	2.29	17.81

CONCLUSIONS AND REMARKS

This study develops the methodology for seismic retrofit prioritization of girder-type bridges based on seismic damage risk and failure cost analysis. The validity of the developed methodology is verified in comparison with the results of the existing methodology applied in Korea. The retrofit priority is examined with various selected model bridges. The most vulnerable components are selected to be retrofitted to improve seismic performance accordingly. In addition, the priority of the retrofitted bridges is revaluated.

The basic procedure of the developed methodology is as follows: (1) An advanced simulation method is developed based on a simplified mechanical bridge model, which can consider the damage states of various vulnerable components as well as the other major phenomena in seismic behaviors of a bridge. (2) Considering the probabilistic distribution of damage indices and the seismic hazard during a bridge service life, the damage possibility of vulnerable components against predefined failure limit state is calculated. The damage index of each vulnerable component is evaluated by using the simplified bridge model. (3) To reflect the relative importance of structural components or bridges, weighting factors are proposed. The weighting factors are determined using the failure cost function formulated for bridges. (4) The overall damage risk of a bridge is obtained from the damage probabilities and weighting factors of vulnerable components. In the same manner, the ranking indices of bridges is estimated from the overall damage risk and weighting factors of bridges. (5) Finally, the seismic retrofit priority of bridges is determined from the ranking index.

From comparison of the existing and developed methodologies, the developed methodology is found to give more specific subdivided priority according to the seismic behavior characteristics of the bridges than the existing methodology. Based on various simulation results, the developed methodology in this study is appropriate in evaluating the priority of the existing and retrofitted bridges as well as in the analysis of retrofitting effects of the existing bridges.

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