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LIFE-CYCLE COST ANALYSIS FOR THE SEISMIC ISOLATION OF BRIDGES IN A REGION OF LOW TO MODERATE SEISMICITY

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SUMMARY

A nonlinear approach for the life-cycle cost (LCC) analysis is proposed. Computational procedure for the analysis of LCC for seismically isolated bridges in a region of low to moderate seismicity is established. To compute the failure probability of critical structural components, most probable failure modes for the structure-isolator system are defined as unseating failure of a superstructure, local shear failure of an isolator, and damage of a pier. Multi-level damage state for a pier is introduced according to the level and type of visual damages and the level of corresponding damage result. Since the relationship between the damage states and the damage index of a pier structure virtually does not exist, or has not yet been established, especially for a region of low to moderate seismicity, a correlation between the damage index and the damage state of a pier structure is established by performing quasi-static cyclic loading test. The probability that a certain level of damage state occurs at a pier is calculated from nonlinear analyses for thousands of artificially generated earthquake records. Damage probability matrix is then constructed for a specific combination of seismic conditions such as acceleration and site condition specified in design codes. The proposed procedure has been applied to the optimal design of seismically isolated bridge based on the minimum LCC. It has also been used for investigating the effect of using different return period of design earthquakes, as is suggested in the NEHRP Provisions (1998). Detailed examples will be presented in the paper.

INTRODUCTION

Seismic isolation is often used for bridges in a region of low to moderate seismicity in order to reduce high construction cost usually caused by seismic performance requirements which have been normally developed for a region of high seismicity. However, considering the uncertainty and risk in such a region, it is important to analyze the life-time cost-effectiveness of the seismic isolation [1]. For this purpose, a nonlinear approach for the life-cycle cost (LCC) analysis is proposed. Computational procedure for the analysis of LCC consists of the following steps: modeling of input ground motion; structural modeling; computing failure probability of critical structural components; defining and evaluating LCC function. To compute the failure probability of critical structural components, the most probable failure modes for the

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structure-isolator system are defined as an unseating failure of a superstructure, local shear failure of an isolator, and damage of a pier. Since the level and type of damage of a pier strongly affects the expected damage cost, multi-level damage state for a pier is introduced, according to the level and type of visual damages such as the size and distribution of cracks, spalling of concrete, failure of rebar, and the level of corresponding damage result or repairability. Since the relationship between the damage states and the damage index of a pier structure virtually does not exist, or has not yet been established, especially for a region of low to moderate seismicity, a correlation between the damage index and the damage state of a pier structure was established by performing quasi-static cyclic loading test for identifying "visual damage" and numerical simulation of the same test for computing "damage index". The probability that a certain level of damage state occurs at a pier can be calculated from nonlinear analyses for thousands of artificially generated earthquake records. Some stochastic processes and stochastical linearization method can be adopted to assume the probability distribution of damage index and simplify the complexity of computation. Damage probability matrix is then constructed for a specific combination of seismic conditions such as acceleration and site condition specified in design codes. The proposed procedure has been applied to the optimal design of seismically isolated bridge based on the minimum LCC. It has also been used for investigating the effect of using different return period of design earthquakes, as reported in the NEHRP Provisions [2].

MODELING OF INPUT GROUND MOTION

In the evaluation of the probabilistic characteristics of an earthquake excited structure, the probabilistic distribution of a structure can be estimated by the Monte Carlo simulation method, a statistical estimation of the structural response from a sufficient number of deterministic analyses based on artificially generated time histories [3]. Although the Monte Carlo simulation method requires a large number of time history analyses in order to obtain a reliable result, it is apparently the only way to evaluate the reliability of a dynamic system considering the nonlinear structural behavior. In the simulation method, a collection of time histories can be used as an input model for a dynamic analysis in the time domain. This section shall briefly describe the procedures involved in generating time histories.

In general, seismic performance of the structural system highly depends on the magnitudes and the frequency characteristics of ground motion. In the assessment of seismic reliability, therefore, using an appropriate excitation model, capable of reflecting the specific characteristics of the construction site, is necessary for performing a satisfactory estimation. To account for the available site characteristics, in this study, a collection of time histories that are compatible with the response spectra of the AASHTO Standard Specification for Highway Bridges for combinations of various seismic intensities and soil profile types are generated using the method developed by Koh et. al.[4]. The site-dependent input ground motion can be obtained by iteratively improving a frequency content component such that the empirical response spectrum based on the time history matches the target response spectrum of the site.

STRUCTURAL MODELING

For the nonlinear time history analysis, seismically isolated bridges can be modeled as a 2-DOFs (Figure 1) or a multi-DOFs model. In this study, only a 2-DOFs model was considered and a multi-DOFs model could be easily applied to this approach for a more precise design or feasibility study.

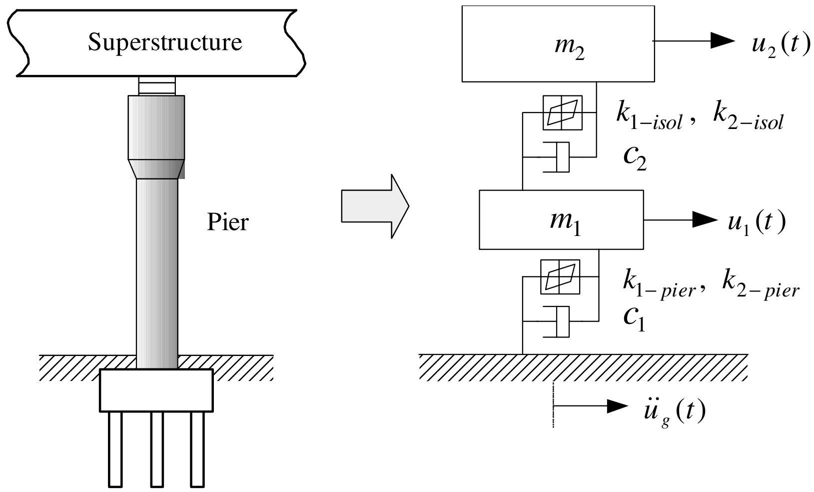

Figure 1. 2-DOFs model and multi-DOFs model of seismically isolated bridges

Ductility of pier structures constitutes an essential seismic capacity in bridges, particularly in non-isolated bridges. Therefore, ductility of pier must be considered to calculate the failure probability and evaluate the cost-effectiveness since piers of isolated and non-isolated bridges may show a relatively different nonlinear behavior. In the present analysis, the non-linearity of pier was modeled as a bilinear hysteretic curve corresponding to push over analysis results. Figure 2 shows an example of push over analysis results of multi-DOFs pier model and the approximated bilinear (elasto-plastic) model of the pier model. Isolation system used in most practical applications can be modeled as either a 'damped linear' system or a nonlinear hysteretic isolation system. In this study, we used a nonlinear isolation system which is characterized by the pre-yielding stiffness k_{1_isol}, and the post-yielding stiffness k_{2_isol}. In our numerical simulation, we took the pre-yielding stiffness, k_{1_isol} as one of design variables for the integrated structure-isolator system, and assumed that the value of post-yielding stiffness k_{2_isol} is 1.0% of k_{1_isol}.

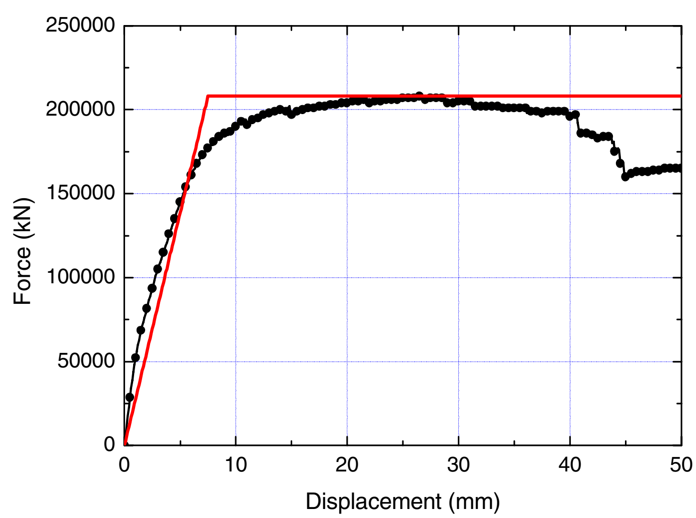

Figure 2. Bilinear model of pier

FAILURE/DAMAGE PROBABILITY ESTIMATION

We defined three different failure modes most likely to occur for the structure-isolator system, namely unseating failure of a superstructure, local shear failure of an isolator, and multi-level damage state of a pier. As a simple failure-safety model for the unseating failure and the isolator's shear failure, we defined the limit states of the responses of superstructure and isolator, respectively, in terms of displacement at relevant DOFs. However, since the expected damage cost of a seismically isolated bridge strongly depends on the level and type of damage of a pier, a simple failure-safety model cannot be used in the case of a pier structure. For example, in the previous study, the damage state of a beam structure was classified into 5 categories, according to the level and type of damages such as the size and distribution of cracks, spalling of concrete, and failure of rebar, and the level of corresponding damage result or repairability. A certain type of damage index, such as the Park and Ang's damage index [5], was then used to correlate the computed response of the pier to the damage state.

In general, the relationship between the damage index and the damage state is generally established based on the past damage experience, as was presented for a building structure in [6]. The relationship between the damage state and the damage index of a pier structure virtually does not exist, or has not yet been established. Especially for a region of low to moderate seismicity, it is needed to develop a correlation between the damage index and the damage state of a pier structure. In this study, the correlation was established by performing quasi-static cyclic loading test for identifying "visual damage" and numerical simulation of the same test for computing "damage index," and verified by pseudo-dynamic test (Figure 3). The result of the correlation for the pier structure is presented in Table 1. The probability that a certain level of damage state occurs at a pier was calculated from nonlinear analyses conducted on thousands of artificially generated earthquake records described in the previous chapter. Damage probability matrix was then constructed for a specific combination of seismic conditions such as acceleration and site condition specified in design codes.

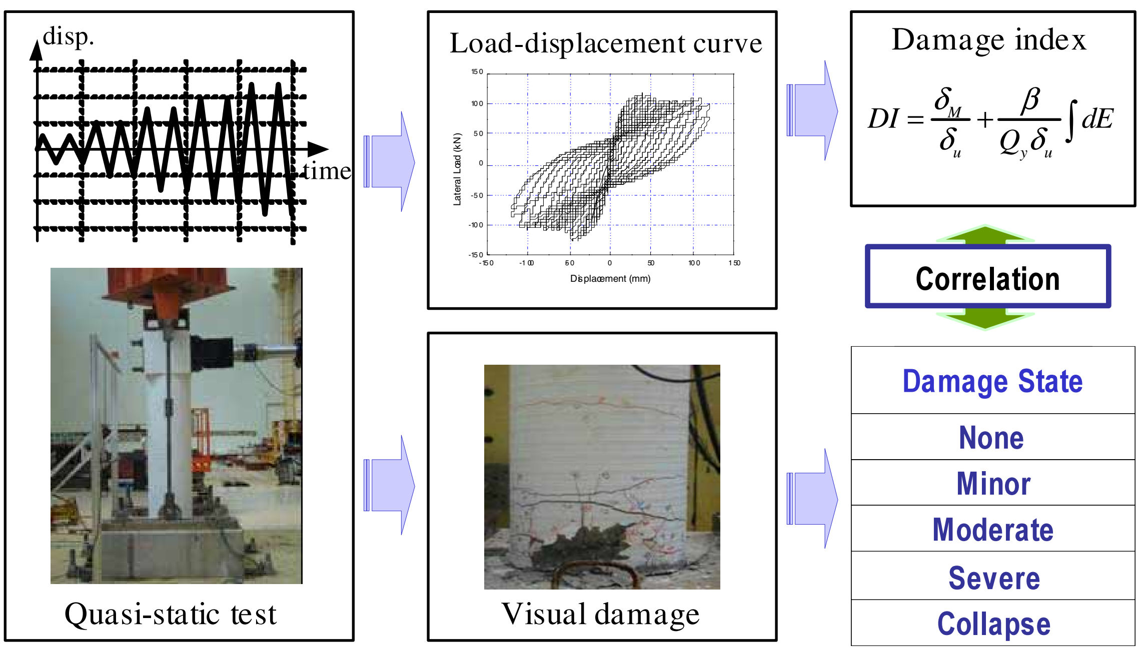

Figure 3. Correlation between damage state and damage index

Table 1. The result of correlation between damage state and damage index

Damage State	Damage Index (DI)		Visual damage	Damage result
	w/special transverse reinforcement of pier	w/o special transverse reinforcement of pier		
None	0.00~0.10	0.00~0.10	None or small number of light cracks, either flexural(90deg) or shear(45deg)	No loss of utility or need not structural repair
Minor	0.10~0.15	0.10~0.20	Widespread light cracking; or a few cracks>1mm wide; or light shear cracks tending to flatten toward 30 deg	Minimum loss of utility, need of a little repair for recovery of design strength
Moderate	0.15~0.45	0.20~0.50	Significant cracking, e.g. 90deg cracks>2mm; 45deg	No use for main repair in a term
Severe	0.45~1.00	0.50~1.00	Very large flexural or shear cracks, usually accompanied by limited spalling of cover concrete	Irreparable damage state, dismantlement
Collapse	>1.00	>1.00	Very severe cracking and spalling of concrete; buckling, kinking or fracture of rebar	Complete or partial collapse of structure

LCC FUNCTION OF SEISMICALLY ISOLATED BRIDGE

The expected value of total life-cycle cost of isolated bridge structure can be evaluated as a sum of the initial construction cost and expected damage cost throughout the life-time of the structure, and expressed as

$$E\left[C_{LCC_{ij}}(k_{p_i},k_{iso_j})\right]=C_{I_{ij}}(k_{p_i},k_{iso_j})+E\left[C_{D_{ij}}(k_{p_i},k_{iso_j})\right] \tag{1}$$

where k_{p_i} and k_{iso_j} are the stiffnesses of pier and isolator of i and j -th design level; $E[C_{LCC_{ij}}]$ and $C_{I_{ij}}$ are the expected life-cycle cost and the initial construction cost for the i -th design level of pier and j -th design level of isolator, respectively. Note that both the initial construction cost and the expected damage cost are expressed in terms of the same design variables, which in this case is the stiffnesses of a pier and an isolator, respectively.

Initial construction cost was estimated by the sum of various cost items such as material cost, labor cost and general cost induced by transportation, insurance, etc. In this study, the proportional ratios of each cost items were evaluated by investigating previous construction costs. Then, total initial construction cost was formulated as a function of direct material cost which could be modeled by using design variables such as stiffnesses of pier and isolator.

Expected damage cost function can be represented as a sum of the expected cost due to the failure of superstructure/isolator and the expected cost due to the damage of a pier as follows:

$$E\left[C_{D_{ij}}(k_{p_i}, k_{iso_j})\right] = E\left[(\text{Failure Cost of Superstructure/isolator}) + (\text{Damage Cost of Pier})\right]$$
$$= \left[\sum_{u=1}^{2} DS_u P_{uij}(k_{p_i}, k_{iso_j}) + \sum_{k=1}^{4} DS_k P_{kij}(k_{p_i}, k_{iso_j}) + C_H + C_R + C_{IR}\right] \cdot \frac{\nu}{\lambda}(1-\exp(-\lambda t_{life})) \quad (2)$$

where $E[C_{D_{ij}}]$ is the expected damage cost of i-th design level of pier and j-th design level of isolator; DS_u and P_u are respectively the damage cost induced by failure of superstructure/isolator and the failure probability of superstructure/isolator; DS_k and P_k are the pier damage cost of k-th damage state and the probability of k-th damage state; C_H, C_R and C_{IR} are the costs due to human loss, traffic congestion delays and indirect local economic loss, respectively; ν is the occurrence rate of earthquake, λ is the discount rate and tlife is the life-cycle of the bridge. In this study, the costs arising from human loss and traffic congestion delays were formulated as a function of damage index.

NUMERICAL EXAMPLES

The proposed nonlinear procedure was applied to the following example (Figure 4) to verify the procedure and investigate the cost-effectiveness for various earthquake conditions. The properties of the structure are shown in Table 2.

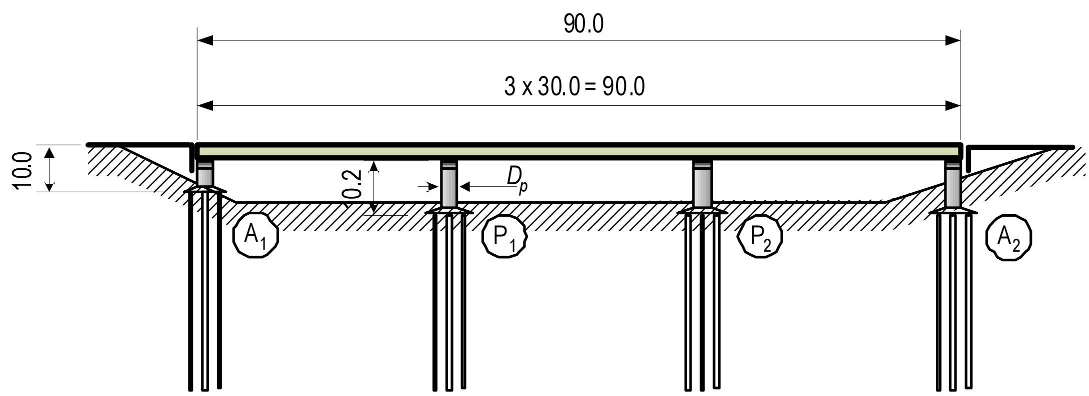

Figure 4. Example of a seismically isolated bridge

Table 2. Properties of the structure

Span length	30 *m*	Height of pier	10.2 *m*
Superstructure weight	1.66×10^7 *N* (per pier)	Reinforcement ratio of pier	2.5 %
Damping ratio of pier	5 %	Damping ratio of isolator	20 %

To evaluate the relative cost-effectiveness of a seismically isolated bridge against a non-isolated bridge, the cost-effectiveness index can be defined as follows.

$$E_{iso/non} = \frac{E[C_{iso}]_{\min}}{E[C_{non}]_{\min}} \quad (3)$$

where $E[C_{iso}]_{\min}$ and $E[C_{non}]_{iso}$ are the minimum LCCs optimized for an isolated bridge and a non-isolated bridge, respectively. According to the definition of the cost-effectiveness index, the smaller the index is the higher cost-effectiveness of seismically isolated bridges. We can also conclude that a seismically isolated bridge is more cost-effective than a non-isolated system if the cost-effectiveness index is less than 1.

Figure 5 shows the evaluation result for the cost-effectiveness of the isolated bridge according to the acceleration level and soil condition. As shown in the figure, cost-effectiveness is consistent with regardless of soil types in the case of lower acceleration coefficients. A guide specification for seismic isolation design of AASHTO [7] also specifies that site studies are recommended only when the acceleration coefficient exceeds 0.29. In the case of higher acceleration coefficients, soft soil condition reduces drastically the cost-effectiveness of seismic isolation and the use of isolation under such conditions may not be economically appropriate in a region of high seismicity.

The last revision of the NEHRP Provisions [2] contains rather innovative proposals on the definition of the design ground motion especially for a region of moderate seismicity. A major point is the decision to base the definition of the design action on the hazard having a probability of 2 percent in 50 years (Return period T_R=2,500 years), instead of the previous and customary 10 percent in 50 years (T_R =475 years). However, for practical design, it is recommended that the design ground motion is obtained by multiplying the spectral ordinates having a T_R =2,500 years by a factor of 2/3 in many situations [8]. Analysis result using the proposed procedure for the example bridge (Figure 4) indicates that the optimal design variable and corresponding LCC in the case of using the 2/3 scaled ground motion are almost the same as those using the full scale ground motion of T_R =475 years, as shown in Figure 6. The optimal design variable and corresponding LCC of full scale ground motion have much larger values than those for the ground motion of T_R =475 years.

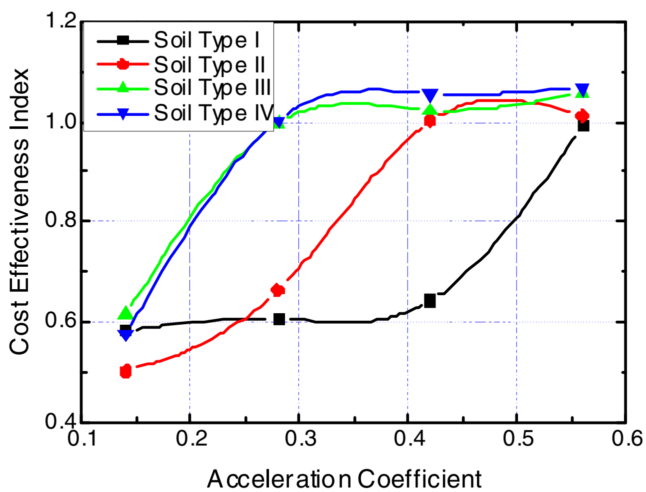

Figure 5. The result of cost-effectiveness evaluation

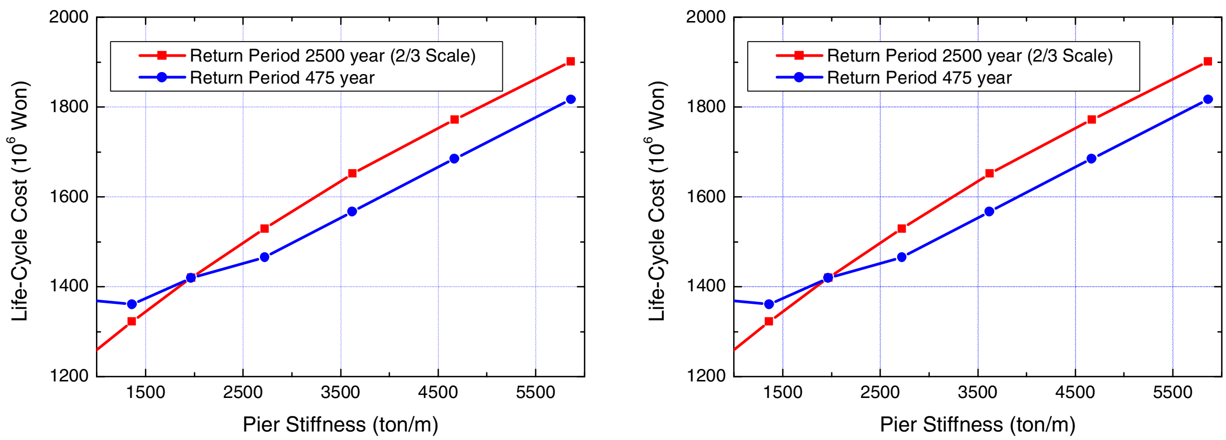

Figure 6. LCC minimized design for 2500 and 475 years of return period of ground motion

CONCLUSIONS

In this paper we presented a nonlinear procedure for the cost-effectiveness analysis and optimal design for the seismic isolation of bridges based on the Life-Cycle Cost concept. The procedure uses a nonlinear time history analyses, including modeling of input ground motion; nonlinear structural modeling for pier and isolator; computing failure probability of critical structural components; and defining and minimizing LCC function. Correlation between multi-level damage state and damage index was also established. Design and analysis examples showed that the present method is capable of being effectively used not only to provide rational basis for the cost-effectiveness investigation on the use of isolation but also to optimize the design variables of the isolated structural system. LCC-based design concept can also be used in seismic design of structures with other supplementary damping devices. The present method is more suitable for a region of low to moderate seismicity, considering the uncertainty and risk in such a region, and also, it fits well with the performance- or consequence-based seismic design concept. According to the specific numerical examples, the seismic isolation system is more cost-effective in a region of low to moderate seismicity than in a region of high seismicity. It has also been found that more flexible isolator can be used especially in a region of low to moderate seismicity and a pier in such a region may be designed to behave elastically so as to fully eliminate possible damages during earthquakes.

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