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COST EFFECTIVENESS OF SEISMIC ISOLATION FOR BRIDGES IN LOW AND MODERATE SEISMIC REGION

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SUMMARY

In order to evaluate the cost effectiveness of seismic isolation for bridges in low and moderate seismic region, a method of calculating minimum life-cycle cost of seismic-isolated bridges under specific acceleration level and soil condition is developed. Input ground motion is modeled as spectral density function compatible with response spectrum for combination of acceleration coefficient and site coefficient. Failure probability is calculated by spectrum analysis based on random vibration theories to simplify repetitive calculations in the minimization procedure. Ductility of piers and its effects on cost effectiveness are considered by stochastic linearization method. Cost function and cost effectiveness index are defined by taking into consideration the characteristics of seismic isolated bridges. Limit states for calculation of failure probability are defined on superstructure, isolator and pier, respectively. The results of example design and analysis show that seismic isolation is more cost-effective in low and moderate seismic region than in high seismic region. The correlation was weak between soil types and the cost effectiveness of the seismic isolation system in low and moderate seismic region, but which was strong in high seismic region.

INTRODUCTION

Seismic isolation is being used as an alternative seismic design technology for various kinds of infrastructures. However, there are few researches on the evaluation of cost effectiveness for seismic isolated bridges even though numerous researches have been performed on cost effectiveness of structural systems such as buildings, bridges, pool structures [Koh, Park and Song, 1999], etc. Particularly, there is a need to study the cost effectiveness of seismic isolation system in low and moderate seismic regions because alternative technologies or design concepts are desired to reduce high cost usually caused by seismic performance requirement in such regions.

Some previous researches on the topic involved parametric studies to evaluate cost reduction of seismic isolation system quantitatively by using global behavior of common bridge configuration [Parducci and Materazzi, 1995]. However, cost effectiveness evaluation should be performed using optimal bridge configuration with minimum life-cycle cost based on cost comparison analyses in order to evaluate the merit and cost effectiveness of isolation effectively [Chang and Liu, 1997]. Moreover, to evaluate cost effectiveness of seismic isolation in low and moderate seismic region, the method should be made by considering the effects of ground acceleration amplitude and soil conditions.

In this study, a method of cost effectiveness evaluation for seismic-isolated bridges based on minimum life-cycle cost concept is developed. This evaluation method also includes the effect of ground acceleration amplitude and soil conditions. By using this method, cost effectiveness of seismic-isolated bridges in low and moderate seismic region is evaluated and its characteristics with ground acceleration amplitude, soil conditions and damage scales are discussed.

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LIFE-CYCLE COST

Life-Cycle Cost Concept

Life-cycle cost concept is a useful measure for optimal design and cost effectiveness evaluation of structures against natural hazards such as earthquakes. Total life-cycle cost includes initial cost of construction and expected damage cost during the structure's life (Figure 1). Damage cost reduces with increasing of structural reliability. However, initial cost increases for more reliable and conservative structural design. There exists an optimal set of design variables that can minimize the total life-cycle cost, and the minimized total life-cycle cost can be used for the evaluation of cost effectiveness of the structural system.

In order to apply this concept to seismic-isolated bridges, cost functions should be defined with appropriate design variables, and a method should be developed which can estimate the minimum life-cycle cost under specific condition.

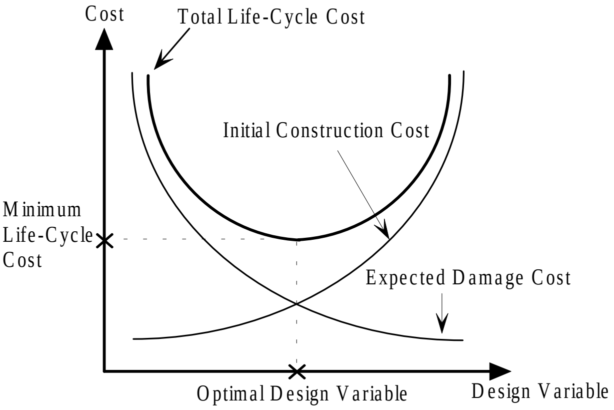

Figure 1. Life-cycle Cost Concept

Structure Modeling of Seismic-Isolated Bridges

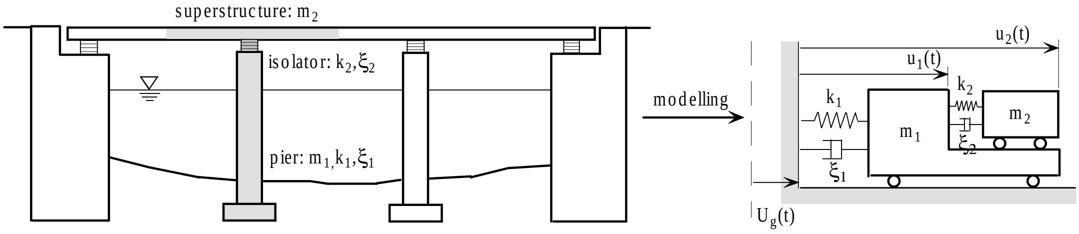

Figure 2. 2-DOF model of a seismic-isolated bridge

In this study, failure probability is calculated using 2-DOF linear model of a seismic-isolated bridge (Figure 2) to perform the repetitive calculations more easily in minimization procedure. The equation of motion is described as follows.

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{u}_1 \\ \ddot{u}_2 \end{Bmatrix}+\begin{bmatrix} C_1+C_2 & -C_2 \\ -C_2 & C_2 \end{bmatrix}\begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \end{Bmatrix}+\begin{bmatrix} k_1+k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}\begin{Bmatrix} u_1 \\ u_2 \end{Bmatrix}=-\begin{Bmatrix} m_1 \\ m_2 \end{Bmatrix}\ddot{u}_g \tag{1}$$

where m_1,C_1,k_1 are mass, damping coefficient and stiffness of pier, m_2 is mass of superstructure, C_2,k_2 are damping coefficient and stiffness of isolator, $u_1,\dot{u}_1,\ddot{u}_1$ are pier displacement, velocity and acceleration relative to ground, $u_2,\dot{u}_2,\ddot{u}_2$ are superstructure displacement, velocity and acceleration relative to ground respectively and u_g is ground acceleration.

Cost Functions of Seismic-Isolated Bridges

Key design variables used for optimization, or optimal design variables, should be chosen out of all design variables. Using these variables, cost functions are defined and minimized. However, there is no need to include all the variables that produce any cost. Because our concern is the cost differences between the various design choices rather than absolute cost of a design [Warszawski, Gluck and Segal, 1996]. Some design variables are selected for cost evaluation, which lead to significant cost differences with change of structural design. Stiffness of pier (k_1) and isolator (k_2) are selected as important design variables, because these two variables determine the natural period of seismic-isolated bridges, and influence the failure probability significantly. In addition, stiffness of pier k_1 is closely related with the cost of bridges.

Expected value of cost function for seismic-isolated bridges is defined in Eq. (2). The first two terms in the right hand side are initial cost function of pier and isolator, and the last term is expected damage cost function.

$$E\left[C_{iso}\left(k_1,k_2\right)\right]=C_pV_p\left(k_1\right)+C_{iso}V_{iso}\left(k_2\right)+C_d\vec{r}_d\cdot\vec{P}_f\left(k_1,k_2\right)\frac{\nu}{\lambda}\left(1-e^{-\lambda t_{life}}\right) \tag{2}$$

where, k_1 is stiffness of pier, k_2 is stiffness of isolator, C_p is initial cost of pier per unit volume, V_p is volume of pier, C_{iso} is initial cost of isolation, V_{iso} is volume of isolator, C_d is assumed damage scale of the bridge, r_d is vector of damage cost ratios of limit states, $P_f(k_1,k_2)$ is vector of conditional probability of each limit state given occurrence of earthquake, ν is occurrence rate of earthquake, λ is discount rate, and t_{life} is life-cycle of the bridge.

Using the following cost effectiveness index, cost effectiveness of seismic-isolated bridges relative to that of non-isolated bridges can be evaluated. The smaller index presents the higher cost effectiveness.

$$E_{iso/non}=\frac{E\left[C_{iso}\right]_{\min}}{E\left[C_{non}\right]_{\min}}=\frac{V_p\left(k_1^{opt}\right)+r_{iso/p}V_{iso}\left(k_2^{opt}\right)+V_f\vec{r}_d\cdot\vec{P}_f\left(k_1^{opt},k_2^{opt}\right)\frac{\nu}{\lambda}\left(1-e^{-\lambda t_{life}}\right)}{V_p\left(k_1^{opt}\right)+V_fP_f\left(k_1^{opt}\right)\frac{\nu}{\lambda}\left(1-e^{-\lambda t_{life}}\right)} \tag{3}$$

where k_1^{opt}, k_2^{opt} are optimal stiffness of pier and isolator minimizing each life-cycle cost respectively, $r_{iso/p}$ is the ratio of cost of isolator to that of pier with same volume, and V_f is the assumed damage scale regulated in the initial cost of pier per unit volume [Wen and Ang, 1992].

INPUT GROUND MOTION MODELING

In cost effectiveness evaluation methods, input ground motion model is required to reflect characteristics of ground motion such as acceleration scale, soil conditions, etc. There are numerous spectral density function models for spectrum analysis, for example, Kanai-Tajimi, Clough-Penzien, Modified Clough-Penzien, etc. But they have so many parameters to define the characteristics of input motion that it is difficult to find correlations between parameters of a model and practical concerns considered in codes.

To resolve these problems and to provide ground motion models appropriate for the method in this study, input ground motion is modeled as spectral density function compatible with response spectrum for combinations of acceleration and site coefficient specified in AASHTO code [AASHTO, 1997]. The procedure generating the model is illustrated in Figure 3. First, spectral density function is assumed randomly. Time histories of acceleration are generated from the assumed spectral density function by spectral representation method [Shinozuka and Deodatis, 1991].

$$\begin{aligned}
&f^{(j)}(p\Delta t)=\operatorname{Re}\left\{\sum B_n\exp\left[i(n\Delta\omega)(p\Delta t)\right]\right\},\quad p=0,1,\ldots,M-1\\
&B_n=\sqrt{2}A_ne^{i\phi_n^{(j)}},\quad n=0,1,\ldots,M-1\\
&A_n=\left(2S_g(n\Delta\omega)\Delta\omega\right)^{1/2}
\end{aligned} \tag{4}$$

where $f^{(j)}(t)$ is acceleration time history of *j*-th generation, $\varphi_n^{(j)}$ is random variable vector between 0 and 2π used for *j*-th generation, and $S_g(\omega)$ is spectral density function generating time history.

Response spectrum is established by averaging the maximum responses obtained from analyses using the generated time histories. Spectral density function is improved by comparing the established response spectrum to the design response spectrum. Upgrading of spectral density function is continued until the spectral density model converges to the design response spectrum (Figure 3). Such procedures are done with all combinations of acceleration coefficient and site coefficient in the codes. Where, acceleration coefficient and site coefficient is an index representing amplitude of acceleration and the soil types (Table 1) respectively. The soil type makes the difference of frequency content of the ground motion.

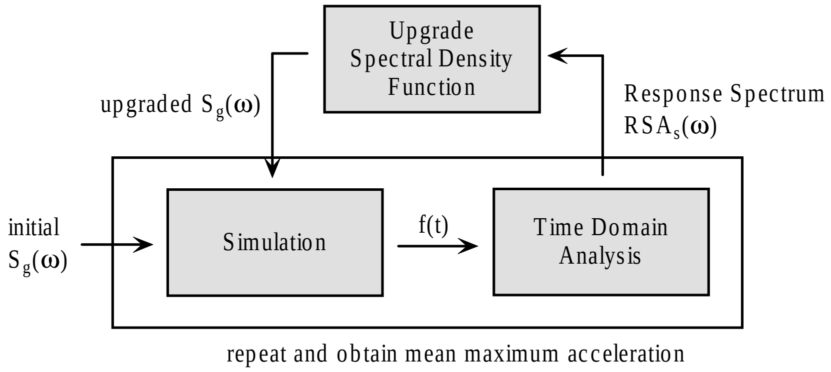

Figure 3. Generation of Spectral Density Model Compatible with Response Spectrum

Table 1. Site Coefficient and Corresponding Soil Properties

Soil Type	Site Coefficient	Soil Properties
I	1.0	1) Rock of any characteristics, either shale-like or crystalline in nature 2) Stiff soil conditions where the soil depth is less than 61m and the soil types overlying rock are stable deposits of sands, gravels or still clays
II	1.5	A profile with stiff clay or deep cohesionless conditions where the soil depth exceeds 61m and the soil types overlying rock are stable deposits of sands, gravels or stiff clays
III	2.0	A profile with soft to medium-stiff clays and sands, characterized by 9m more of soft to medium-stiff clays with or without intervening layers of sand or other cohesionless soils
IV	2.7	A profile with soft clays or silts greater than 12m in depth.

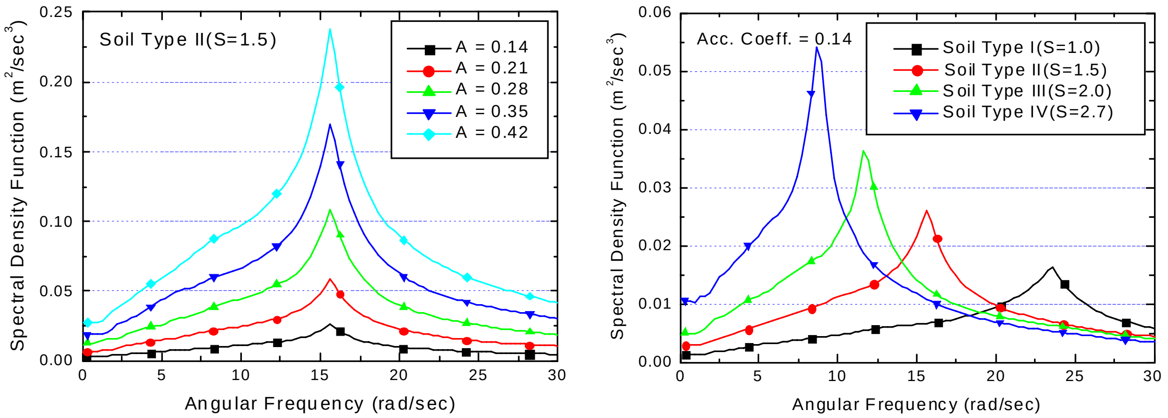

Figure 4. Spectral Density Input Model Compatible According to *A*-*S* pairs

Spectral density functions generated according to acceleration and site coefficient pairs are shown in Figure 4. The scales of spectral density functions are in proportion to acceleration coefficient. As site coefficient increases, peaks of spectral density functions move to long period and the value increases. It reflects the phenomena that soft layer amplifies long period motion. From these results, the spectral density model presented in this study properly reflects the acceleration coefficient and the soil coefficient. The spectral density function corresponding to the combination of acceleration coefficient and site coefficient can be used to evaluate cost effectiveness of seismic-isolated bridges at the specific site.

FAILURE PROBABILITIES

Method for Calculation of Failure Probabilities

Crossing rates of responses over predetermined limit states are calculated as follows [Newland, 1993]. First, transfer function of each response is derived from the equation of motion, Eq. (1). Then, spectral density function of a response is obtained by multiplying its transfer function and spectral density model of input ground motion.

$$S_u(\omega)=\left|H_u(\omega)\right|^2\cdot S_g(\omega) \tag{5}$$

where *u* is the response of which failure probability is calculated, $S_u(\omega)$ is spectral density function of response *u*, $H_u(\omega)$ is the transfer function of u about input ground acceleration, and $S_g(\omega)$ is spectral density function model of ground acceleration generated by the procedure mentioned in Ch. 3.

Standard deviations of responses are calculated by integrating the spectral density functions. Crossing rate of responses over the limit states is calculated as follows under the assumption that input motion is subject to Gaussian distribution.

$$\nu_u=\frac{1}{2\pi}\frac{\sigma_{\dot{u}}}{\sigma_u}\exp\left(-u_{\mathrm{lim}}^2/2\sigma_u^2\right) \tag{6}$$

where ν_u *is crossing rate of response* u, $\sigma_{\dot{u}}$ *is standard deviation of* $\dot{u}$, σ_u *is standard deviation of* u, *and* u_{lim} *is the limit state defined on* u.

Assuming that failure occurrence is subject to Poisson distribution, conditional failure probability for an earthquake is estimated as follows.

$$P_{f_u/eq}=1-\exp\left(-\nu_u t_d\right) \tag{7}$$

where t_d *is duration time of earthquake.*

Stochastic Linearization Method

Ductility of pier should be considered in calculating failure probability because it affects failure probability and cost effectiveness of non-isolated bridges significantly. As spectrum analysis, repetitive calculations are used in this study. The nonlinear behavior of pier and its effects on failure probability are considered by stochastic linearization method [Lutes and Sarkani, 1997]. The coefficients in the linear function minimizing errors from the original nonlinear function are obtained on several assumptions about the behavior of pier. Using this method, the effects of nonlinear property such as ductility of pier can be considered in the linear spectrum analysis.

COST EFFECTIVENESS EVALUATION

Example

To verify the adaptability of the presented method and investigate the general tendency of cost effectiveness in low and moderate seismic region, cost effectiveness index defined in Eq. (3) is calculated for the bridge in Figure 5. Properties of the bridge are shown in Table 2.

Cost Effectiveness with Acceleration Amplitude

Cost effectiveness indices were obtained according to several acceleration coefficients (Figure. 6). At the sites of stiff soil condition such as soil type I, cost effectiveness is in proportion to acceleration coefficient when the assumed damage scale is small. On the contrary, high acceleration level (when A=1.0 in Figure. 6) causes a reduction in cost effectiveness if damage scale is sufficiently large. Such a damage scale means that the bridge is very important, and so a high level of reliability is required. As a result, very important seismic-isolated bridges on stiff soil have higher cost effectiveness in low and moderate seismic region than in high seismic region. Such a trend of cost effectiveness is more clear in the case of soft soil.

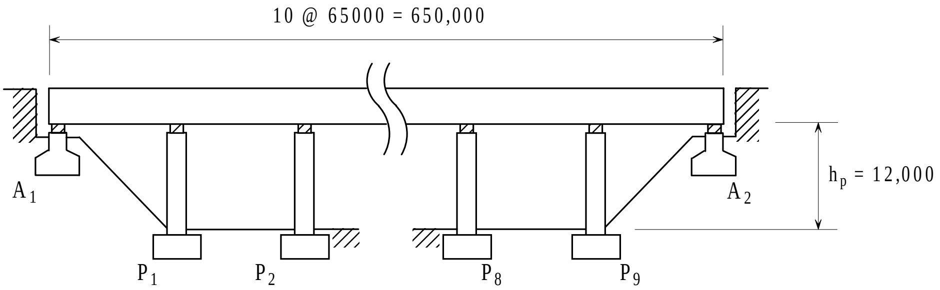

Figure 5. Example of a Seismic-Isolated Bridge

Table 2. Properties of the Bridge in Figure 5

Span length	65 m	Height of pier	12 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 %

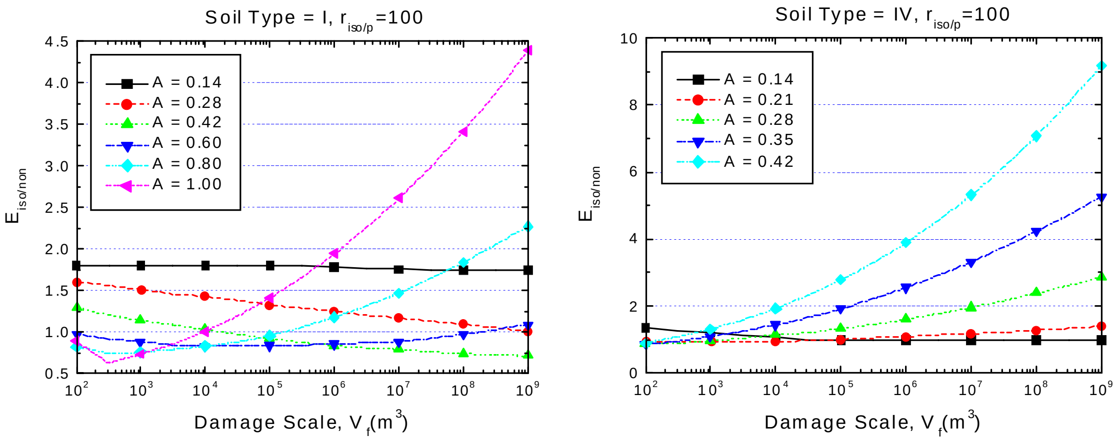

Figure 6. Cost Effectiveness with Acceleration Coefficient

Cost Effectiveness with Soil Conditions

As shown in Figure 7, there are no consistent trends about the effects of soil types in low acceleration region (*A* = 0.14). Guide specifications for seismic isolation design of AASHTO [AASHTO, 1997] also specifies that site studies are recommended only when the acceleration coefficient exceeds 0.29. However, in higher seismic region (A=0.42), soft soil condition reduces cost effectiveness of seismic isolation of bridges.

Sensitivity of Optimal Design Variables

Sensitivity of optimal design variables to damage scales are checked with change of the acceleration amplitude and soil conditions. By the results with A = 0.14 in Figure 8, cost effectiveness of seismic isolation increases with the increase of damage scale in low seismic region. This trend does not vary with soil condition. Besides, cost effectiveness of seismic isolation in soft soil is worse then that of stiff soil in higher seismic region.

If the site is soft soil layer, the application of seismic isolation of bridges in high seismic region is not recommended because of the following reasons. Seismic isolation makes natural period of a structure longer, and dominant earthquake energy in soft soil layer is inclined to long period area. If these two periods are coupled with large amplitude, the seismic performance of the structure becomes significantly worse. On the other hand, the resonance phenomenon is difficult to occur in low and moderate seismic region because of the high damping capacity of the isolation system. Similar results was obtained in this cost effectiveness analysis of seismic isolation for bridges.

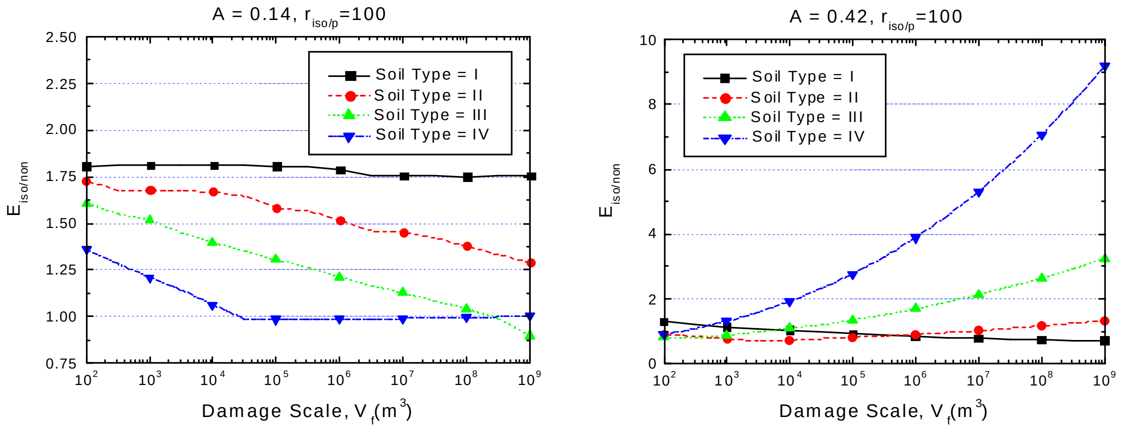

Figure 7. Cost Effectiveness with Soil Types

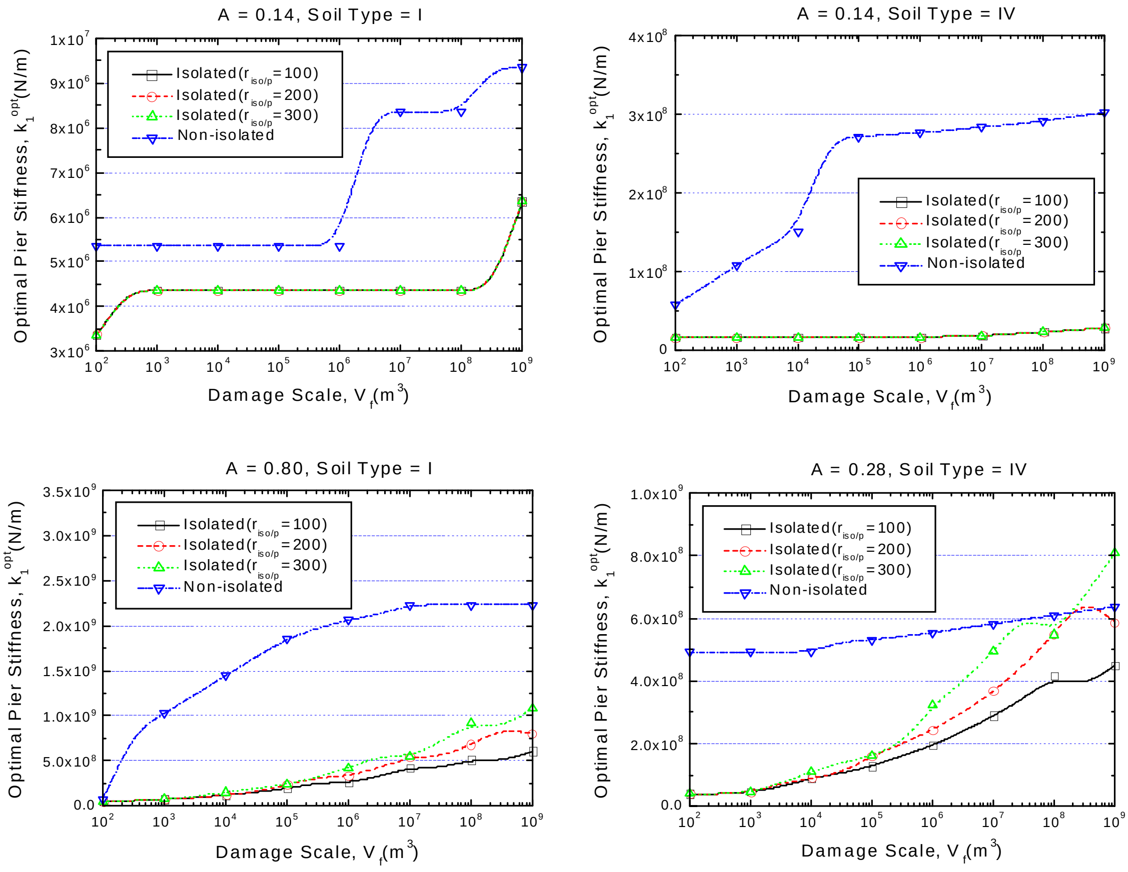

Figure 8. Sensitivity of Optimal Design Variables to Damage Scales

CONCLUSIONS

In order to evaluate the cost effectiveness of seismic isolation for bridges in low and moderate seismic region, a method of calculating minimum life-cycle cost of seismic-isolated bridges under various conditions of seismicity such as the intensity and site effects is developed. The procedure also can optimize seismic design of seismic-isolated bridges by minimizing life-cycle cost.

Input ground motion is modeled as spectral density function compatible with response spectrum for combination of acceleration coefficient and site coefficient. Failure probability is calculated by spectrum analysis based on random vibration theories to simplify repetitive calculations in the minimization procedure. Ductility of piers and its effects on cost effectiveness are considered by stochastic linearization method. Cost function and cost effectiveness index are defined by taking into consideration the characteristics of seismic isolated bridges. Limit states for calculation of failure probability are defined on superstructure, isolator and pier, respectively.

The results of example design and analysis show that seismic isolation is more cost-effective in low and moderate seismic region than in high seismic region. This trend of cost effectiveness of seismic isolation is clear in the case of very important bridges.

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