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LIFE-CYCLE COST EFFECTIVENESS OF BASE-ISOLATED WOODEN HOUSE IN SEISMICALLY ACTIVE REGION

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SUMMARY

This paper presents the life-cycle cost effectiveness of a base-isolated wooden house in Japan. This house is exposed to intensive seismic hazards since it is located near the seismic source of Miyagi-ken-oki Earthquake (magnitude is about 7.5), which was forecasted to occur in 99 % probability within this 30 years. Strong ground motions are expected around the selected house when the earthquake occurs. In order to examine the effectiveness of the base-isolated system, the life-cycle costs of two design alternatives are compared: one is the base-fixed house and the other is base-isolated one. The analysis demonstrates that the initial investment to the base-isolation system reduces the life-cycle cost imposed on the owner of the house. Based on such a result, the engineers can persuade owners of buildings to purchase base-isolation systems, particularly, in seismically active regions. The life-cycle costs are estimated utilizing the equation formulated by the first author. This equation provides owners of buildings with rational decision-makings because it can directly reflect newly announced information on activities of surrounding seismic sources, and can make use of up-to-date simulation techniques developed in the related academic fields such as seismology, geotechnical engineering, structural engineering and social economics.

INTRODUCTION

Headquarters for Earthquake Research Promotion (HERP [1]) organized by Japanese government has been announcing the probability of large earthquakes that are expected to occur around Japan. Among them some were forecasted to occur in very high probabilities within this 30 years, e.g., 99% for Miyagi-ken-oki earthquake (M_W = 7.5), 50% for Tonankai earthquake (M_W = 8.1) and 40% Nankai earthquake (M_W = 8.4). Near such a seismic source, the owner of a building should prepare for the soon-coming earthquake in design of a new building or upgrade of existing one. For a private building, however, the owner should do that upon his/her own budget, and thus he/she would be reluctant to invest in the future events. Structural researchers and engineers have been developing “hard” seismic technologies, for example, strong and ductile frames, baring walls, energy dissipation dampers, base isolation systems and

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so on. On the other hand, “soft” technology to persuade the owners of buildings to invest in such sophisticated “hard” technology is not sufficiently developed. This causes the barrier to the efficient spread of safer buildings in our societies.

Under those situations, Takahashi [2, 3] proposed a seismic risk management methodology aiming to persuade owners to invest in appropriate seismic systems. There seismic risk management is defined as a decision problem among multiple design alternatives. Alternatives for seismic design or upgrade may be a bare frame designed according to a design code, with strong and ductile frames, with baring walls, with energy dissipation systems, with base isolation systems, purchasing earthquake insurances, or combinations of some of them. One alternative that minimizes the total expenditure, i.e., the life-cycle cost, of the building owner including the initial cost and the cumulative damage cost due to all earthquakes that occur during the lifetime of the building, is chosen as an optimum selection. The expected life-cycle cost of each alternative is formulated so that we can directly introduce earthquake probabilities in the surrounding seismic sources, which have been reported by HERP [1] or WGCEP [4]. In addition, for the computation of the expected damage cost due to earthquakes of a given magnitude, we can utilize the up-to-date simulation techniques developed in the relevant fields such as seismology, geotechnical engineering, structural engineering, and social economics.

As an example, the proposed methodology was applied to an actual office building newly constructed in Tokyo [2, 3]. The life-cycle costs of two alternatives are compared: one is a bare steel moment frame and the other is the same frame with energy dissipation dampers. Through the case study, it is demonstrated that a passive energy dissipation system using oil dampers is effective in reducing the life-cycle cost.

It is more important to apply the risk management methodology to inducing the owners of buildings in seismically active regions to adopt appropriate investments. This paper, following the above case study in Tokyo, demonstrates the life-cycle cost effectiveness of a base-isolation system in a wooden house, by comparing with that of a usual base-fixed one. The selected house is located near the seismic source of Miyagi-ken-oki earthquake (recall 99% within this 30 years), and forecasted to be shaken by a strong ground motion once the earthquake occurs [1]. In the computation of the expected life-cycle costs, the up-to-date simulation models developed in the related academic fields are fully utilized, and one of the best solutions at this time is provided.

SEISMIC RISK MANAGEMENT BASED ON LIFE-CYCLE COST

Seismic risk management of a building is here defined as a decision problem among multiple design alternatives as shown in Figure 1. One alternative that minimizes the life-cycle cost (LCC) can be chosen as the optimum selection. LCC is the sum of the initial cost and the damage costs incurred by future earthquakes, and can be regarded as a random variable. According to the minimum expected loss criterion in the decision theory (Ang [5]), one alternative minimizing the expected LCC is optimum. Then we should compute the expected LCC of each alternative.

Assume a renewal process for earthquake occurrences in the seismic sources surrounding the building under consideration. Takahashi [2, 3] formulated the expected life-cycle cost of each alternative, $E[C_L]$, as

$$E\left[C_L\right] = C_I + \sum_{all\ sources} \sum_{j=1}^{K} E\left[C_D(m_j)\right] \int_{t_0}^{t_0+t_{life}} Q^{t-t_0} \sum_{n=1}^{\infty} f_{W_n}(t, m_j | W_1 > t_0) dt \qquad (1)$$

where C_I is the initial cost, $E[\ .\ ]$ is the expectation operator, $C_D(m_j)$ is the damage cost due to earthquakes with magnitude m_j, t_0 is the starting time of the building, t_{life} is the lifetime of the building, $Q = 1/(1+d)$ is the discount factor, d is the discount rate, and $f_{Wn}(t,m_j|W_1>t_0)$ is the PDF of the waiting time to the nth earthquake of magnitude m_j on the condition that there is no earthquake between the last earthquake and time t_0. In the above expression, the inner sum is over the discretized set of magnitudes and the outer sum is over all seismic sources to be considered in the analysis.

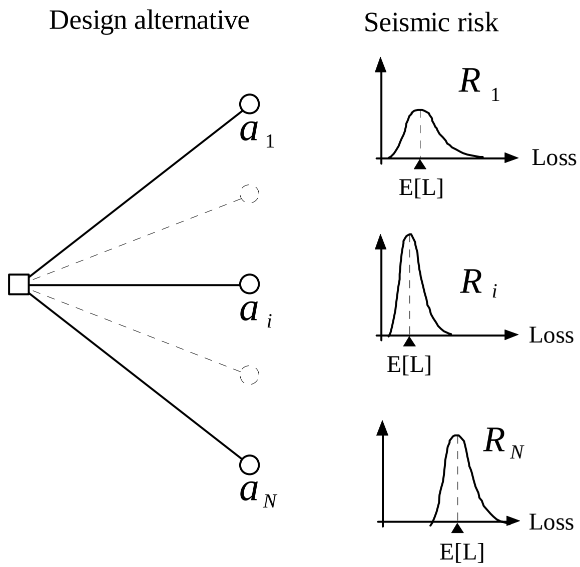


Figure 1. Decision tree in seismic risk management

When assuming the Poisson process, which is one particular form of the renewal process, Equation (1) reduces to [2, 3]

$$E\left[C_L\right] = C_I + \frac{Q^{t_{life}} - 1}{\ln Q} \times \sum_{all\ sources} \sum_{j=1}^{K} \nu(m_j) \cdot E\left[C_D(m_j)\right] \qquad \text{for } Q \neq 1 \tag{2a}$$

$$E\left[C_L\right] = C_I + t_{life} \times \sum_{all\ sources} \sum_{j=1}^{K} \nu(m_j) \cdot E\left[C_D(m_j)\right] \qquad \text{for } Q = 1 \tag{2b}$$

where $\nu(m_j)$ is the mean occurrence rate of an earthquake with magnitude m_j. The terms $f_{Wn}(t,m_j|W_1>t_0)$ and $\nu(m_j)$ in Equations (1) and (2) correspond to probabilistic models of occurrence of earthquakes. The form in (1) can account not only for historical earthquake data but also for newly acquired information on activities of seismic sources, such as WGCEP [4] and HERP [1], in estimating the life-cycle cost of buildings.

In Equation (1) or (2), the expected damage cost $E[C_D(m_j)]$ caused by earthquakes with a specific magnitude m_j in a given source should be computed. Relevant processes are illustrated in Figure 2: fault rupture in the seismic source, elastic wave propagation, surface soil amplification, dynamic response of the building, and generation of damage costs. Monte Carlo simulations are performed in this study to simulate a sequence of these processes. Each simulated sample is a realization derived from a set of probabilistic models describing those processes considering their uncertainties. An adequate number of samples are generated for each magnitude and source, and the damage cost of each sample is computed. The expectation of the sample population is then estimated as

$$E[C_D(m_j)] = \frac{1}{N_S} \sum_{i=1}^{N_S} c_{D(i)}(m_j) \tag{3}$$

where N_S is the number of samples, and $c_{D(i)}(m_j)$ is the damage cost of the ith sample. To simulate these processes, we can freely select analytical models developed in relevant fields of seismology, geotechnical engineering, structural engineering and social economics. Thus, the term $E[C_D(m_j)]$ in Equation (1) or (2) can always include up-to-date knowledge in the respective fields.

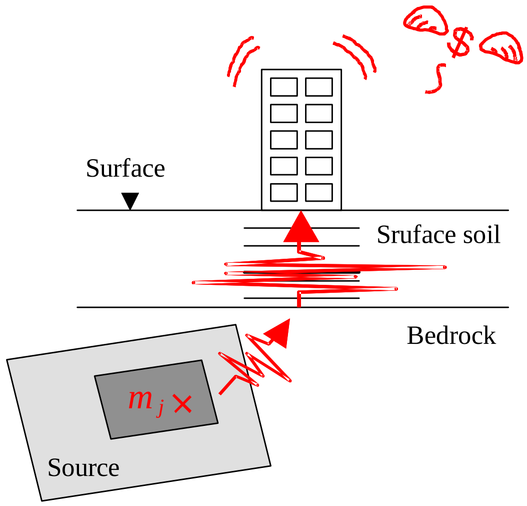


Figure 2. Events from fault rupture to generation of damage costs

As mentioned above, in theory, any simulation model can be used in estimating $E[C_D(m_j)]$. However, in practice, an engineer is supposed to prepare a “menu” including several “courses” corresponding to needs from clients, i.e., building owners. Some clients may need the most exact solutions with much money, but others with small budgets may request rough estimation. Figure 3 gives an example of a menu with three courses, cheap, middle and expensive. If the expensive course is ordered, an engineer can spend much in the specification of the parameters and the computation, and gives one of the most reliable solutions. On the other hand, if cheap course is requested, the engineer can show the result instantly and cheaply with simple simulations. Figure 3 is just a current example, and it should be updated by reflecting the progress of simulation models and computation technologies in relevant academic fields aiming to provide clients with better decision-makings with less expense. Just for an example, the simulation models in the “middle course” in Figure 3 are utilized in the case study shown in the next section.

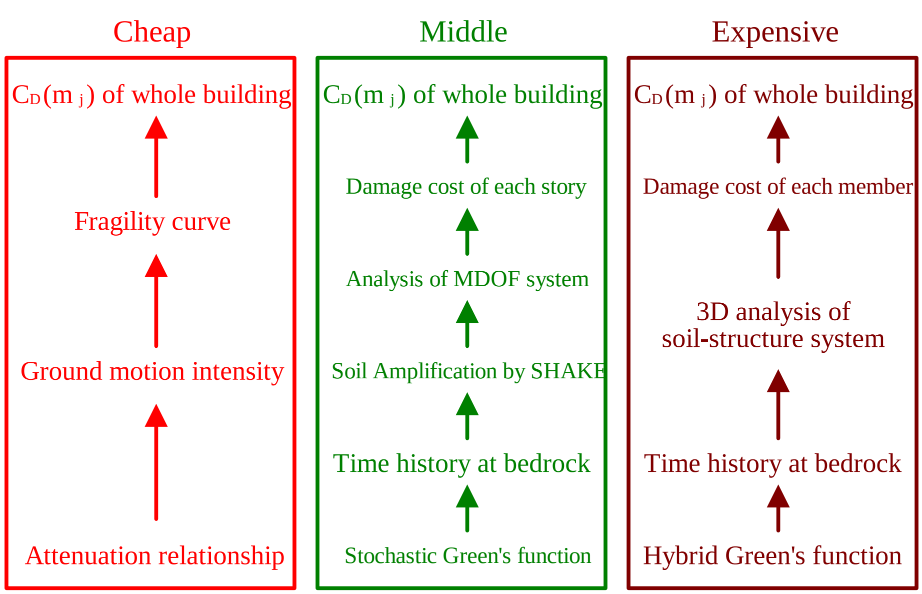


Figure 3. Example of current simulation models for the computation of $E[C_D(m_j)]$

LIFE-CYCLE COST EFFECIVENESS OF BASE-ISOLATED WOODEN HOUSE

Selected house

A typical two-story house constructed in Japan is considered here. The house has a total area of about 150 m^2. The structure consists of Japanese traditional frames the strength of which sufficiently satisfy the Japanese building code. To avoid strong ground motion, the base isolation system is adopted. Six isolators of high-damping rubber and 4 frictional sliders that support the whole weight of the upper structure are installed at the base of the house. In this case study, the life-cycle costs of two design alternatives are compared: a_1 is the hypothetical normal house (assuming base-fixed) and a_2 is the actual base-isolated one. The lifetime of the house is assumed to be 30 years, that is, t_{life} = 30 years in Equation (1) or (2). The initial cost of the base-fixed house is $300,000, and the base-isolation system costs $26,000 (8.7% of the cost of the upper structure). Then the initial costs of a_1 and a_2 are $300,000 and $326,000, respectively. Assuming this house accommodates a family of four, and then the value of the contents of the building is assumed to be $160,000 based on Sompo Japan [6] (a Japanese insurance company).

Figure 4. Selected wooden house in Sendai city in Miyagi prefecture, Japan

Activity of seismic source

In this case study, a seismic source shown as a simple rectangle in Figure 5 is considered. This is a boundary between the Pacific plate and the Eurasia plate, where Miyagi-ken-oki earthquakes (magnitude is about 7.5) have repeatedly occurred. The depth to the upper edge of the rectangle source is 20 km, strike is 190° from the north, and dip is 20° from the horizon. Using typical earthquake catalogues, Usami [7], Utsu [8, 9] and JMA [10], the activity of the seismic source is investigated for events up to A.D.1984, A.D.1985 - A.D.1925, and A.D.1926 - A.D.2000, respectively. The epicenters of the selected earthquakes are plotted in Figure 5. The earthquakes are classified into three groups according to their magnitudes, $5.0 \leq m < 6.0$, $6.0 \leq m < 7.0$ and $7.0 \leq m < 8.0$, and their representative magnitude values are m_j = 5.5, 6.5 and 7.5, respectively. Based on those historical data, we modeled the activities of the seismic source using the Poisson model and a non-Poisson renewal model.

Figure 6(a) demonstrates the relationship between time and magnitude of earthquakes around the specified seismic source shown in Figure 5. Figure 6(b) shows the mean annual occurrence rates for the three categories of earthquakes, which are estimated using the data shown in Figure 6(a). In the case of m_3 = 7.5, the return period is estimated to be 37.1 years (HERP [1]), and $\nu(7.5) = 0.027$ (= 1/37.1) is specified.

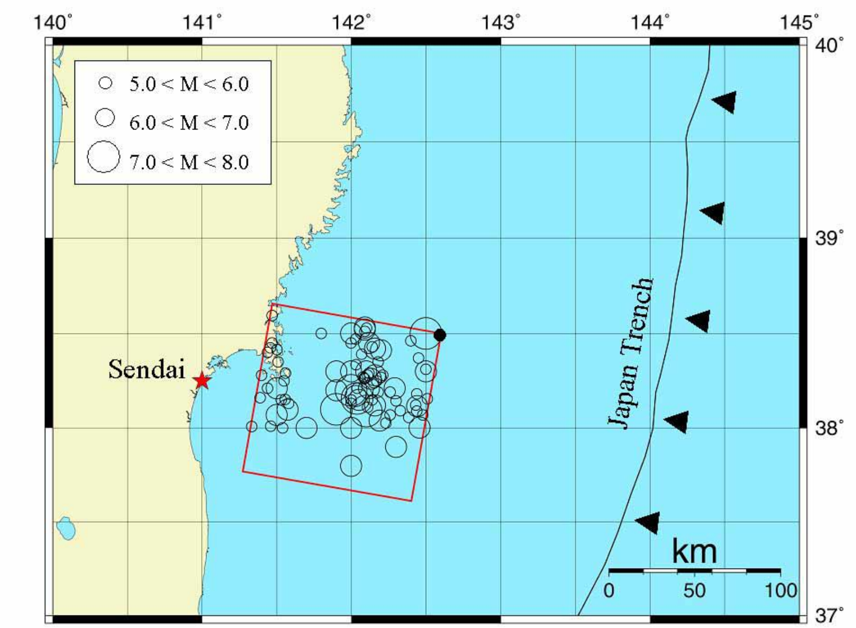
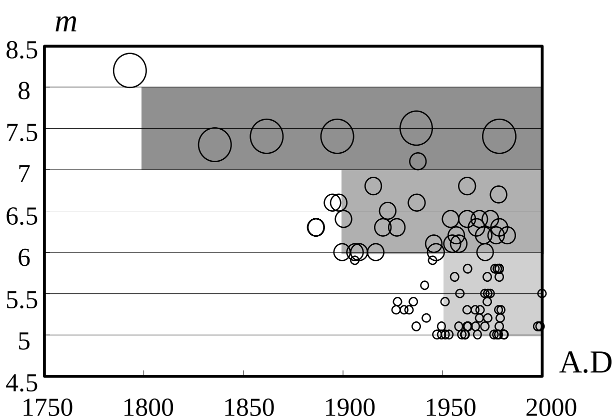
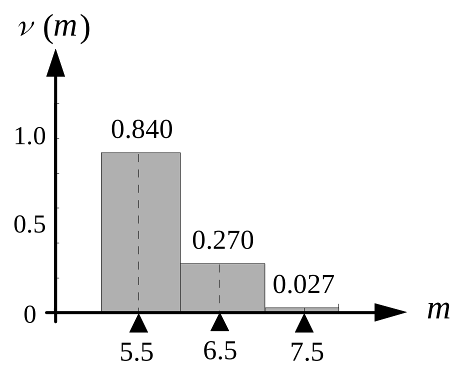


Figure 5. Seismic source (square), epicenter of past earthquake (circle) and house site (star)



(a) Time-magnitude



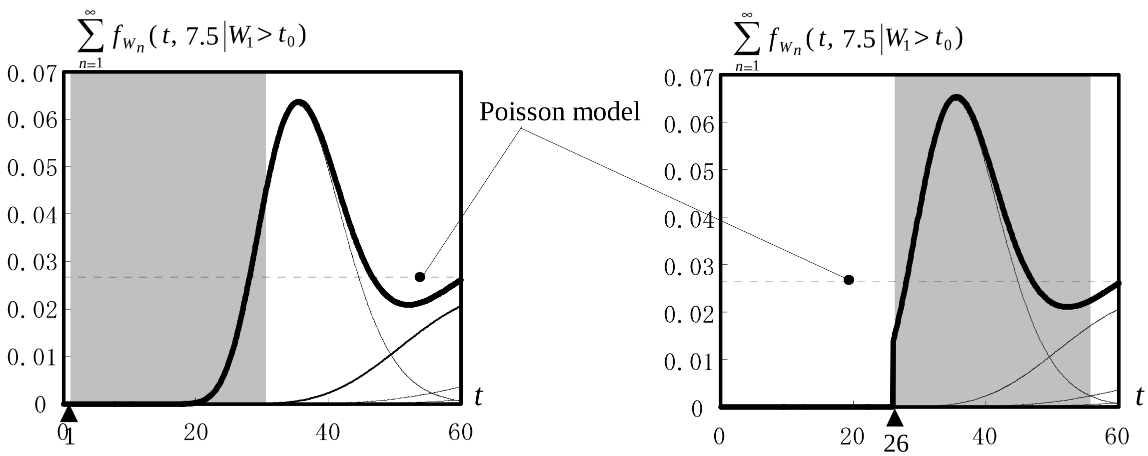
(b) Magnitude-annual occurrence rate

Figure 6. Activity of seismic source under consideration

The Poisson model is adequate for earthquakes that frequently occur during the lifetime of the building (m_1 = 5.5 and m_2 = 6.5 earthquakes). However, for infrequent earthquakes (m_3 = 7.5 earthquakes), a non-Poisson renewal model may be more appropriate. Among non-Poisson renewal models, the Brownian Passage Time (BPT) model (Matthews [11]) has been applied to long-term estimation of earthquake probabilities by WGCEP [4] and HERP [1]. According to this model, the inter-arrival time between successive earthquakes of magnitude m_3 = 7.5 is

$$f_T(t,7.5) = \sqrt{\frac{\mu}{2\pi\alpha^2 t^3}} \exp\left\{-\frac{(t-\mu)^2}{2\mu\alpha^2 t}\right\} \tag{4}$$

where μ is the mean and α is the aperiodicity (= coefficient of variation). Based on HERP [1], μ = 37.1 years and α = 0.177 are assumed. The last event occurred in A.D. 1978. The updated PDF, $\sum_{n=1}^{5} f_{W_n}(t,7.5 | W_1 > t_0)$, is computed numerically using the rules of conditional probability. Figure 7(a) shows the occurrence rate $\sum_{n=1}^{\infty} f_{W_n}(t, 7.5 | W_1 > t_0) \approx \sum_{n=1}^{5} f_{W_n}(t, 7.5 | W_1 > t_0)$ for t_0 = 1.0 year, i.e., the starting time of the house is assumed to be A.D. 1979 (one year after the last Miyagi-ken-oki earthquake in 1978). Figure 7(b) is for t_0 = 26 years, that is, A.D. 2004. The mean annual occurrence rate of the Poisson model, which is the constant $\nu(7.5) = 0.027$, is also displayed in the figures. From Figure 7(a), we can see that the Poisson model overestimates the occurrence rate during the lifetime (t_{life} = 30 years: shaded segment) in the case of t_0 = 1 year. On the other hand, Figure 7(b) demonstrates that the Poisson model underestimates the occurrence rate in the case of t_0 = 26 years.

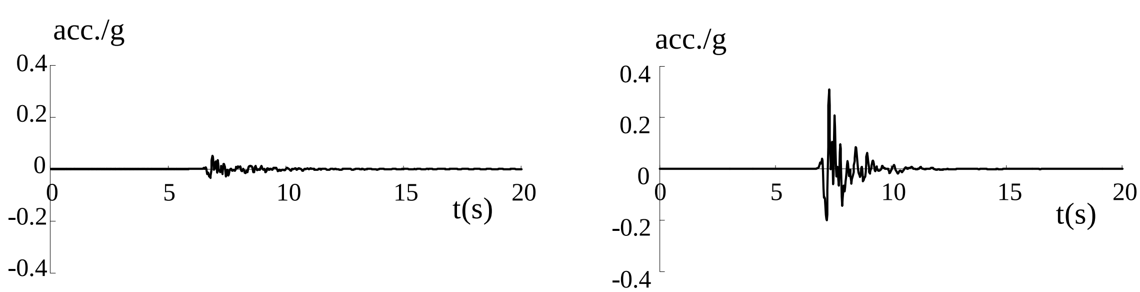


(a) t_0 = 1 year (1 year after previous event) **(a) t_0 = 26 years (26 years after previous event)**

Figure 7. Occurrence rate for Miyagi-ken-oki Earthquake (m_3 = 7.5)

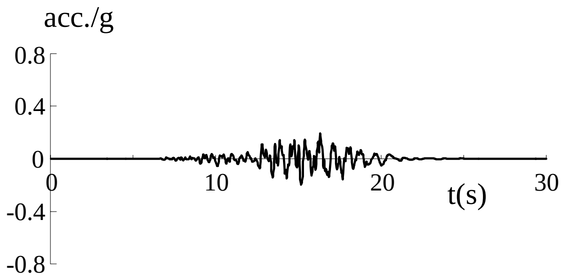
Simulation for $E[C_D(m_j)]$

To estimate $E[C_D(m_j)]$ in Equation (1) or (2), Monte Carlo simulation with 100 samples is performed for each of the magnitudes, m_j = 5.5, 6.5 and 7.5, considering uncertainties associated with the relevant processes illustrated in Figure 2. The "middle course" simulation models shown in Figure 3 are utilized here. Stochastic ground motions are generated utilizing the finite-fault stochastic Green's function method (Boore [12] and Kamae [13]) for fault rupture and elastic wave propagation. The parameters are specified by referring to HERP [1]. SHAKE (Schnabel [14]) is used for the computation of surface soil amplification. The house structure is modeled as a two-degree of freedom system. Nonlinear dynamic response analysis is performed by applying a sample ground motion to a sample structure model. The non-linear behavior of the frame is modeled as a parallel combination of bilinear- and slip-hysteresis developed by Kawai [15] and Isoda [16]. Based on the response, a damage cost is estimated for each sample using fragility curves and recovery time by FEMA [17]. Some results of Monte Carlo simulations with 100 samples are shown in Figures 8 through 13.

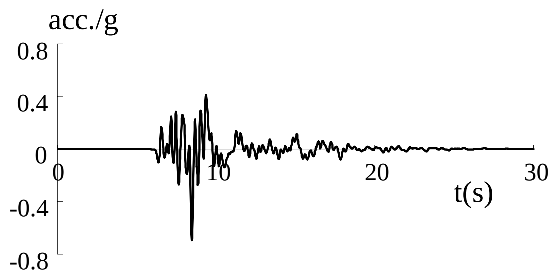


(a) With smallest PGA of 100 samples **(b) With largest PGA of 100 samples**

Figure 8. Acceleration of ground motion at soil surface (m_1 = 5.5)

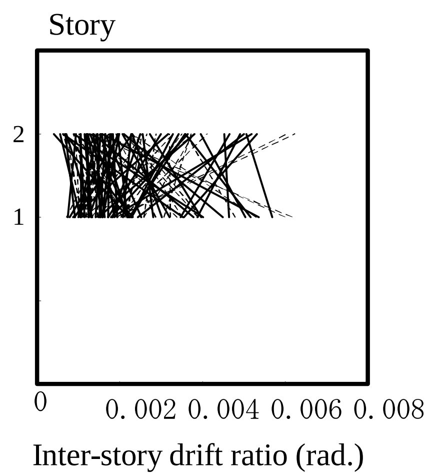


(a) With smallest PGA of 100 samples

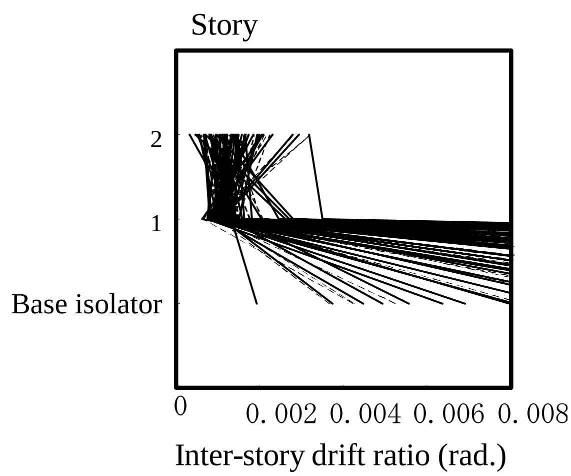


(b) With largest PGA of 100 samples

Figure 9. Acceleration of ground motion at soil surface (m_3 = 7.5)

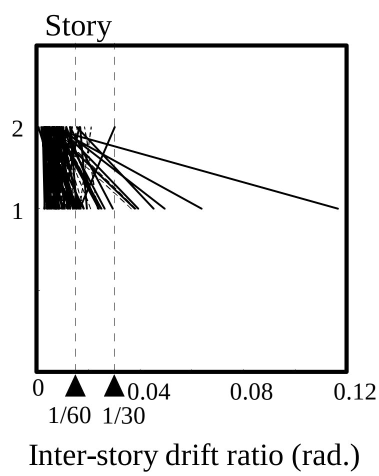


(a) Base-fixed

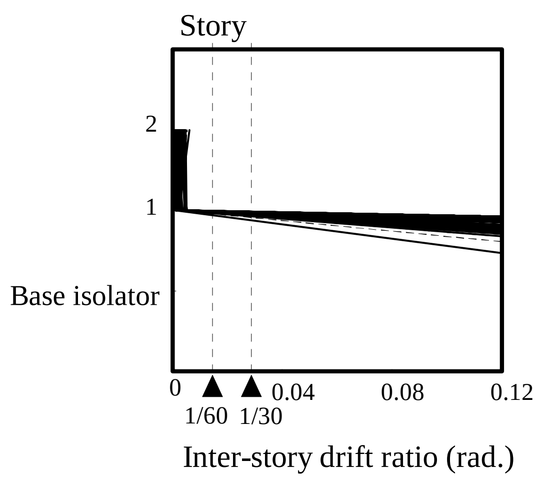


(b) Base-isolated

Figure 10. Inter-story drift ratio of house (m_1 = 5.5)

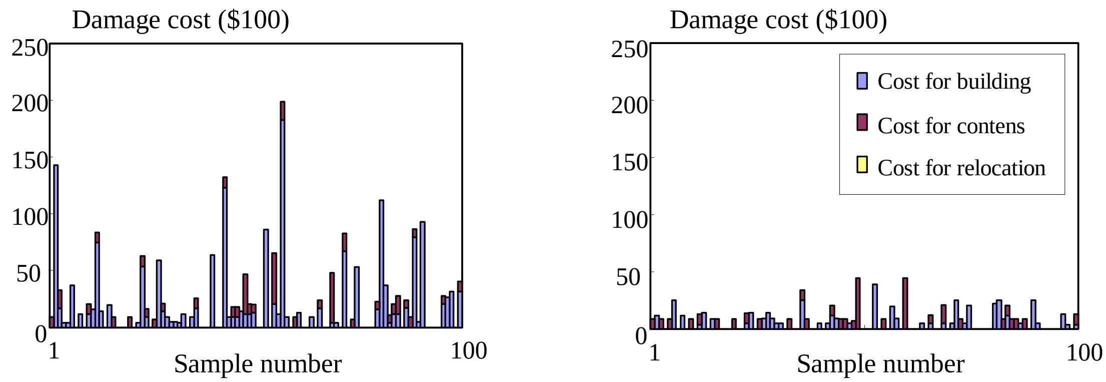


(a) Base-fixed



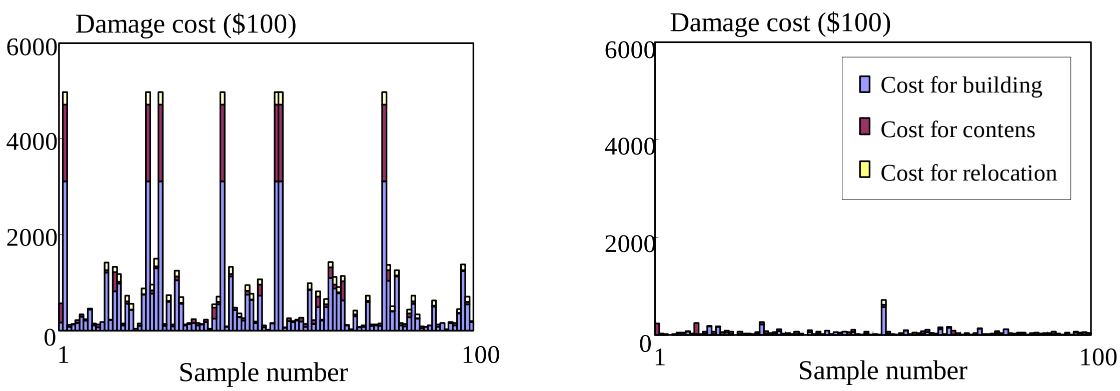
(b) Base-isolated

Figure 11. Inter-story drift ratio of house (m_3 = 7.5)



(a) Base-fixed **(b) Base-isolated**

Figure 12. Damage costs of 100 samples (m_1 = 5.5)



(a) Base-fixed **(b) Base-isolated**

Figure 13. Damage costs of 100 samples (m_3 = 7.5)

Substituting the damage costs of the 100 samples shown in Figures 12 and 13 into Equation (3), their expectations, $E[C_D(m_j)]$, can be estimated as Figure 14. The figure demonstrates that the reduction of the expected damage cost by the base-isolation system is greater as the magnitude of the earthquake becomes larger.

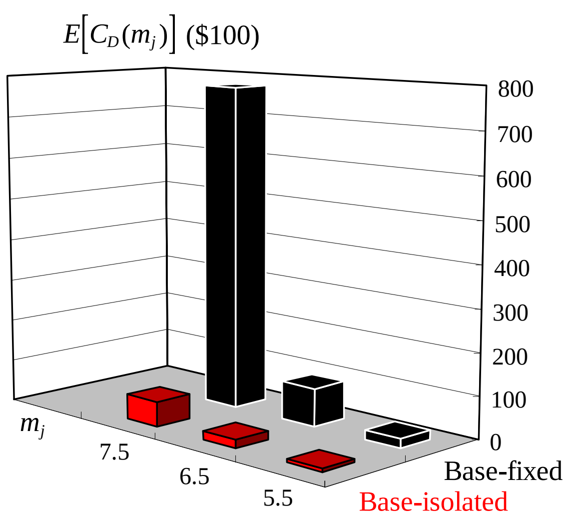


Figure 14. Expected damage cost

Expected life-cycle cost

Figure 15 shows the relationship between the lifetime of the building (t_{life}) and the expected life-cycle costs ($E[C_L]$) estimated by substituting $\nu(m_j)$ in Figure 6(b) and $E[C_D(m_j)]$ in Figure 14 into Equation (2). They intersect at 5.2 years after the starting time. This indicates that the installation of the base-isolation system is effective from the aspect of life-cycle cost if the lifetime is longer than 5.2 years. The difference at the end of the lifetime (t_{life} = 30 years) is $125,000. This is an expected profit to the decision maker gained by adopting dampers in this risk management.

Similarly, the life-cycle costs assuming the BPT model are computed using Equation (1), and Figures 16 and 17 illustrate the results for t_0 = 1 year (A.D. 1979) and t_0 = 26 years (A.D. 2004), respectively. The results for the Poisson model (Figure 15) are also displayed using dotted lines for comparison. In the case of t_0 = 1 year, the slopes become less steep than the dotted lines because the Poisson model overestimates the occurrence rate of m_3 = 7.5 earthquakes as shown in Figure 7(a). Consequently, the crossing point occurs later and the gain and residual risk at the end of the lifetime are reduced. Opposite results are observed in the case of t_0 = 26 years because the Poisson model underestimates the seismic activity. This indicates that the life-cycle cost effectiveness becomes larger as time passes without the expected earthquake, i.e., as the seismic source becomes more active. Although the numbers are different in each case, it is evident that the optimal alternative remains the same for all models.

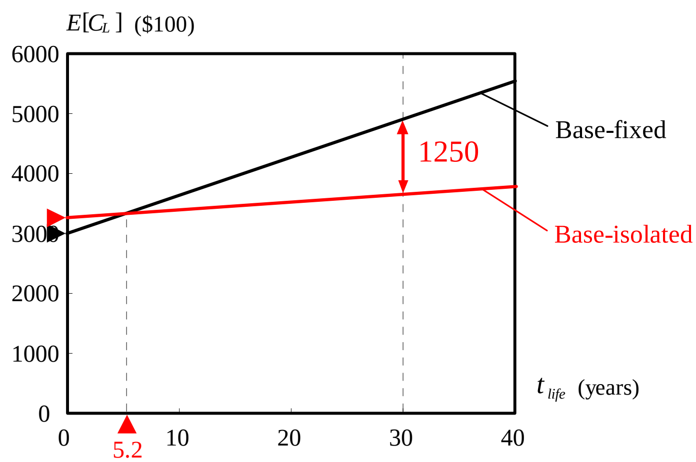


Figure 15. Service time vs. expected LCC (Poisson model)

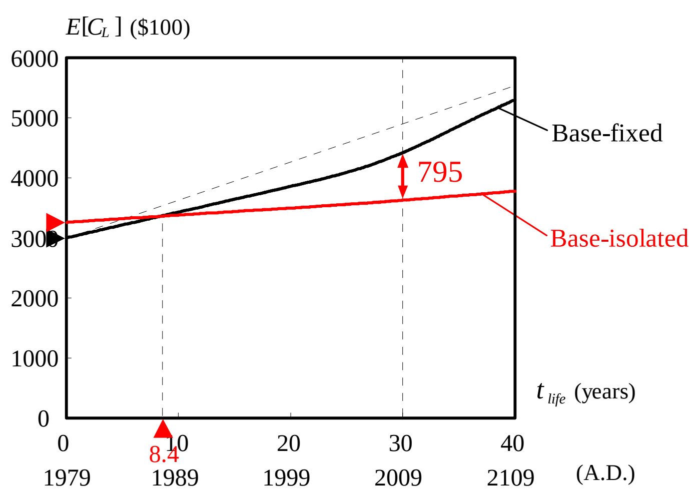


Figure 16. Service time vs. expected LCC (BPT model, t_0 = 1 year)

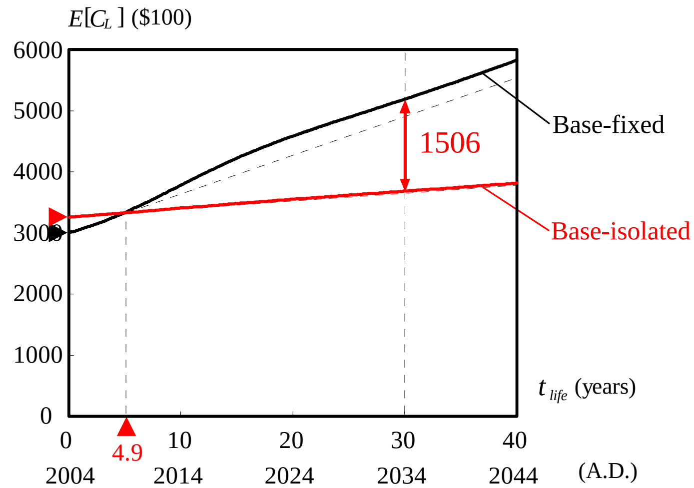


Figure 17. Service time vs. expected LCC (BPT model, t_0 = 26 years)

CONCLUSIONS

It is important to show the cost effectiveness of appropriate design alternatives and to induce the owners of buildings to invest in them in design of new buildings or update of existing ones. In particular, it is urgent in the regions around the seismic sources where large earthquakes are forecasted to occur in high probabilities.

As one example, the life-cycle cost effectiveness of the base isolation system adopted in a typical wooden house is examined. The house under consideration is located near the seismic source of Miyagi-ken-oki earthquake (M_W = 7.5), which was forecasted to occur in 99% within this 30 years. The life-cycle cost of the base-isolated house is compared with that of the base-fixed one. Their life-cycle costs are estimated by introducing the probabilistic model used by HERP [1], and utilizing the up-to-date simulation models developed in seismology, geotechnical engineering, structural engineering and social economics. This case study demonstrates that the life-cycle cost can be reduced by adopting the base isolation system.

This study is just one example, but a typical prototype to show owners of buildings the life-cycle cost effectiveness of appropriate investments. Similar studies are applicable to various kinds of buildings such as city halls, schools, offices, commercial buildings, plants and residential buildings. Those will contribute to motivating owners of new or existing buildings, and to spreading safer structures, particularly, in seismically active regions for the sake of urban disaster mitigation.

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