Earthquake countermeasures for wood houses to mitigate seismic loss and total cost

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ABSTRACT: It is said that plate subduction-zone earthquakes and inland shallow earthquakes may occur in several decades in Japan. However, many residents do not try to perform seismic retrofit, even if their wooden houses have poor seismic performance and will suffer extensive damage if a severe earthquake occurs. In order to motivate residents to implement an effective earthquake countermeasure for their houses, this paper proposes evaluation indexes to select the most cost effective earthquake countermeasure for their own houses. Then, we have performed some case studies changing location and earthquake countermeasure techniques and timing to demonstrate the validity of the proposed indexes and to discuss how to prepare for the big earthquakes.

1 INTRODUCTION

After the 1995 Hyogo-ken Nanbu Earthquake, the seismic activity in Japan is activated, and large earthquakes, such as the Noto Hanto Earthquake and the Niigata Chuetsu-Oki Earthquake in 2007, that cause wooden houses the extensive damage happen frequently in various places frequently. In addition, it is believed certain that the huge ocean-trench earthquake such as Nankai and Tonankai earthquakes will occur within several decades in the future. Therefore, to mitigate the earthquake damage of the wooden houses during those large earthquakes is thought to be a high-priority issue for the earthquake disaster prevention measures from the viewpoint of the life and property protection.

Especially, it is necessary for the wooden houses where the extensive damage is assumed when a large earthquake occurs to perform seismic retrofit. However, seismic retrofit to prepare in approaching earthquake are not advanced enough in the assumption earthquake-stricken region. Although the subsidy system of seismic retrofit by the country and municipality has increased, it is a current state that there are a lot of wooden houses which do not performed seismic retrofit even if their seismic performance is low now.

This is attributed to the fact that residents are suspicious of the effects of the seismic retrofit, or they can not afford the cost.

The factor which can evaluate a seismic loss corresponding to dwelling performance and study it that can mitigate the seismic loss has been proposed so far (Ishida. H,2004 & Takahashi. Y,2005 & Fuku-shima. S, 2005).

Though an aseismic performance of the wooden house is pointed out the possibility of decreasing as time ticks away by the influence of the biodeterioration such as the wood destroying fungus and termite and so on (Hayashi. Y, 2004), this effect is not considered in their seismic risk evaluation.

On the other hand, in the seismic hazard, the probability of the earthquake occurrence is different according to the scenario earthquake, and as for the same scenario earthquake it changes at time goes by. But the time change of the seismic hazard is not considered in their seismic risk evaluation.

Since the in-service period of the wooden house is much shorter than the interval of the earthquake occurrence, it is important for thinking about the seismic damage decrease plan in the wooden house to consider what type of the seismic retrofit work so well and when it must implement.

From the above-mentioned this research aims to construct the methodology which considers seismic environment and seismic occurrence time in each regions, and the time change of an aseismic performance of the wooden house, makes the residents themselves be able to recognize the existing seismic risk of their wooden houses and the effect of the damage mitigation of their wooden houses by the seismic retrofit and the maintenance, and becomes possible for the residents to make a choice of the seismic retrofit.

Therefore, this paper focuses the decrease of a expected loss and life cycle cost (total cost) of the
wooden house by the seismic retrofit, and considers its method, timing, and cost which can implement the seismic retrofit effectively and economically.

At first, in the second chapter, this paper describes a seismic damage evaluation method and a seismic risk evaluation method considering the seismic hazard and an aged deterioration of the wooden house, then draws on an Expected Seismic Loss.

Next, in the third chapter, it proposes two evaluation indexes, a Loss Reduction Index and a Total Cost Reduction Index, based on the preceding chapter. The two indexes can evaluate the cost-effective seismic retrofit and its timing of implementation.

Finally, in the fourth chapter, sensitivity analysis is performed in five cities (Osaka, Kyoto, Nagoya, Tsu, and Kochi in Japan), by using the proposed methods and two evaluation indexes. Seismic hazard is different in each five cities.

In the sensitivity analysis, the focus is appropriated to seismic performance (to strengthening or improving deformation performance) within earthquake countermeasures, and how region, timing, and method of the earthquake countermeasure influences the proposal index is verified at the time of the seismic retrofit. In addition, seismic countermeasures needed by the region where the seismic risk is different are considered by using the result of the sensitivity analysis.

2.2 Earthquake damage level evaluation technique for considering aged deterioration

First, fragility function, probability distribution function (PDF) of damage, considering aged deterioration is explained. The fragility function \( P_{fr} \) with the maximum horizontal deformation angle \( R \) and age \( \tau \) of a wood house can be given by

\[
P_{fr}(R, \tau) = \Phi\left[\ln(R) - \ln(R_m(\tau))\right]/\zeta_R
\]

(1)

Where \( \Phi \) is the cumulative distribution function (CDF) of the standard normal distribution, and \( \ln(R_m(\tau)) \) and \( \zeta_R \) are the average and standard deviation of \( \ln(R) \). The \( R_m(\tau) \) decreases with age \( \tau \) such as \( R_m(\tau) = d(\tau) \cdot R_m(0) \) as shown in Figures 2-3. The reduction factor \( d(\tau) \) is written as

\[
d(\tau) = \max\{\exp\left[-0.7(\tau/\beta \tau_0)^{\frac{3}{2}}\right] \cdot 0.5\}
\]

(2)

where the \( \beta \tau_0 \) is the durable years determined by construction method of wooden house, regional climate, and maintenance condition based on the Durability Design Guideline (DDG) (Ministry of Land, 1986). At this time, in the aged deterioration curve inverted reduction factor from the statistical damage data of wooden houses, the durable years are, for example, estimated as \( \beta \tau_0 = 33 \) for houses in Kobe and \( \beta \tau_0 = 108 \) for those in Tottori based on the DGG. \( \beta \tau_0 \) is assumed as \( \beta = 1 \) for the sake of simplicity below.

To calculate the maximum deformation angle \( R \), a house is modeled by the SDOF system. If the restoring force-displacement relation is assumed to be bilinear, equivalent natural period \( T \) and damping factor \( h \) for the maximum deformation angle \( R \) can be expressed as follows using the equivalent mass \( \mu \) and equivalent height \( H_e \) yield base shear coefficient \( C_v \) and yield deformation angle \( R_y = 1/100 \).

\[
T(R) = 2\pi\sqrt{H_eR\mu/(C_vR_y)}
\]

\[
h(R) = 0.2\left[1 - 1/\sqrt{R/R_y}\right] + 0.05
\]

(3)

Each earthquake source change every year and the seismic hazard is calculated every elapsed year in consideration of the time change.

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\]

(3)
The yield base shear coefficient $C_i$ is calculated from the seismic capacity evaluation of an existing house. As for a scenario earthquake, the maximum deformation angle $R$ in Eq.(1) can be evaluated by making the acceleration response spectrum $S_a(T,h)$ of the estimated ground motions equal to $C_i g/F_h(R)$, where $F_h(R)=1.5/(1+10h(R))$.

On the other hand, the probability density functions with the maximum deformation angle $R$ in Eq.(1) are written as that with the peak ground velocity (PGV) $v$ for the simplicity of hazard analyses. In that process, acceleration response spectra are related to $v$ as

$$S_a(T,h(R)) = 2v(2\pi/T)F_a(R)$$  \hspace{1cm} (4)

Based on the above assumptions, the fragility function with the PGV $v$ can be approximated by the following equations (Saratani, A, et al, 2006).

$$P_{f_i}(v,\tau) = \Phi \left[ \ln(v) - \ln(v_0(\tau)) \right]/\zeta_v(\tau)$$  \hspace{1cm} (5)

where

$$v_0(\tau) = \left[ \frac{2500gH_s C_y}{H_s \mu F_h(R_0(\tau))^2} \right] \cdot R_0(\tau)^{1/2}$$

$$\zeta_v(\tau) = \frac{\zeta_R}{2} + \ln \left[ F_h(R_0(\tau)/\epsilon_0) \right]/F_h(R_0(\tau))$$

### 2.3 Earthquake risk evaluation technique based on earthquake hazard

Next, a seismic risk evaluation method considering the aged deterioration of a wooden house is proposed. The seismic damage loss expectation of a wooden house is evaluated as shown in the following.

At first, the seismic loss of the wooden house when an earthquake occurred $\tau$ years after by using a seismic loss function $L_f(v,\tau)$ calculated as the product-sum of damage probability $P_{f_i}(v,\tau)$ given by Eq.(5) and loss $L_i$ for each damage level $i$ (Fig. 4).

$$L_f(v,\tau) = \sum_{i} P_{f_i}(v,\tau) \cdot L_i(\tau)$$  \hspace{1cm} (6)

Here, ratio of the loss to an asset value (Shown in Chapter 4) corresponding to each damage level is constant without relying on age $\tau$, but the asset value decreases by age $\tau$. Therefore, loss $L_i$ decreases by age $\tau$.

In the seismic hazard analyses, on the other hand, the expected value of seismic loss by many earthquakes over the in-service period of the wood house is estimated considering local seismic hazard and interannual change in occurrence probability of earthquakes, which are evaluated by the Subcommittee for Long-term Evaluations of the Earthquake Research Committee of the Headquarters for Earthquake Research Promotion in Japan (J-SHIS, 2006). In the calculation of the seismic loss function in Eq. (6), $\tau=t_i$ is substituted into Eq.(5) where $t_i$ satisfies

$$\int_{0}^{t_i} d(\tau)d\tau = d(t_i)$$

Namely, the seismic performance of the wooden house is assumed to be equal to the average value during the $t$ years of in-service period for simplicity (Fig. 5). This assumption can show the difference of the expected seismic loss which is discussed below by the difference at the durable years even if the in-service period becomes long. The exceedance probability $P(v,t)$ of the PGVs of earthquakes occurred around a site being more than $v$ once at least during $t$ years is given as follows, if probability density function and probability distribution function of the PGV $v$ during in-service period $t$ years are denoted by $f(v, t)$ and $F(v, t)$, respectively.

$$F(v,t) = \int_{-\infty}^{v} f(v,t)dv , \quad P(v,t) = 1 - F(v,t)$$  \hspace{1cm} (7)

In addition, as well as document, the probability of occurrence of a peculiar each earthquake is calculated based on stationary Poisson process for stationary seismic activity model, and based on updating process or BPT distribution on the basis of temporal prediction model for nonstationary seismic activity model.

First, $f(v,t)$ is calculated from a seismic hazard curve $P(v,t)$. Then, the seismic risk density during $t$ years is denoted by $L_f(v,t)f(v,t)$. Finally, the expected seismic loss $ESL(t)$ is given by

$$ESL(t) = \int_{0}^{\infty} L_f(v,t) \cdot f(v,t)dv$$

![Figure 4. Seismic loss function](image)

![Figure 5. Aged deterioration of seismic performance during in-service period](image)

![Figure 6. Expected seismic loss](image)
3 EVALUATION INDEX OF COST-EFFECTIVENESS

3.1 Introduction

Next, it proposes two evaluation indexes, Loss Reduction Index and Total Cost Reduction index, which can evaluate cost-effectiveness based on the expected seismic loss obtained by the preceding chapter. These indexes can evaluate the aged deterioration of the wooden house, and the time change and regional difference of the seismic hazard. In addition, the period when the seismic countermeasures are done is counted based on elapsed years from present. Here, a relation of time series among elapsed years \( u \), in-service period \( t \), age \( \tau \), and durable years \( \tau_0 \) is shown in Figure 7.

3.2 Loss Reduction Index (LRI)

The Loss Reduction Index (LRI) is an index that evaluates how seismic loss decreased by the seismic countermeasure, so it is the expected value function of seismic loss saved on by the seismic countermeasure. The Loss Reduction Index \( LRI(u) \) is defined as

\[
LRI(u) = ESL_b(u) - ESL_a(u)
\]

where \( ESL_b(u) \) is the expected seismic loss without any seismic countermeasures, and \( ESL_a(u) \) is the expected seismic loss with some sort of seismic countermeasures. The fragility function \( P_{fv} \) to \( v \) decreases by doing seismic countermeasures, and as a result the value of ESL decreases. It is shown that the bigger the LRI is, the bigger the seismic loss decreased with seismic countermeasures is, in other words, the safer the wooden house becomes.

3.3 Total Cost Reduction Index (TCRI)

The Total Cost Reduction Index (TCRI) is an index that evaluates how the total of the cost spent on the house by implementing seismic countermeasures is held down, so it is the expected value function of a Total Cost \( TC(u) \) changed by implementing seismic countermeasures. Here, the Total Cost includes initial cost of construction, maintenance cost, and casual loss of houses, and it is a sum of these costs over elapsed years from specified time. In addition, the lower the Total Cost is, the bigger the cost-effectiveness is (Fig. 8). Furthermore, if elapsed years \( u \) correspond to in-service period \( t \) in the Total Cost, the Total Cost is seen as a Life Cycle Cost. The Total Cost \( TC(u) \) is written as

\[
TC(u) = c_0 + ESL(u) + \sum_{j=1}^{u} c_j
\]

where \( c_0 \) is the initial cost, and \( c_j \) is the cost of earthquake countermeasures in the \( j \)-th year. Then, the Total Cost Reduction Index \( TCRI(u) \) is defined as

\[
TCRI(u) = TC_b(u) - TC_a(u)
\]

where \( TC_b(u) \) is the Total Cost without any seismic countermeasures, and \( TC_a(u) \) is the Total Cost with some sort of seismic countermeasures. As the Eq.(10) shows, the TCRI can be indicated a difference between the cost of earthquake countermeasures and the LRI. The bigger the TCRI, the more cost-effective the countermeasures are. Especially, if the TCRI is a positive value, it can be said that the Total Cost is decreased after the countermeasures, and implementing them is economical rather than nothing (Fig. 9).

![Figure 7. A relation of time series.](image1)

![Figure 9. Total Cost Reduction Index.](image2)
4 SENSITIVITY ANALYSIS

4.1 Standard case setting

In this chapter, to measure how time and the method of earthquake countermeasures and difference between regions influence the evaluation indexes, these sensitivities are analyzed.

First of all, the necessary conditions for sensitivity analysis are set as follows.

(a) Sensitivity analysis is applied to five cities, Osaka, Kyoto, Nagoya, Tsu, and Kochi shown in Figure 10, and those seismic hazard curves over in-service period of $t$ years for those cities are shown in Figure 11.

(b) A wooden house is assumed to be newly built in 2006 ($\tau=0$). Initial construction cost of the house $c_0$ is 15 million yen. Yield base shear coefficient $C_y$ is 0.1. Durable years $\beta\tau$ are 25.

(c) Earthquake countermeasure techniques may include seismic retrofitting to strengthening or improving deformation performance, durability enhancement to increase durable years, and rebuilding. Here, the techniques are limited to the seismic retrofitting. The seismic retrofitting to strengthening (Countermeasure A) raises yield base shear coefficient $C_y$ from 0.1 to 0.3 with paying 1.4 million yen (Sato, K, 2006). The seismic retrofitting to improving deformation performance (Countermeasure B) brings aged deterioration curve $R_m(t)$ back to initial value with paying 1.4 million yen, similarly (Table 1).

Table 1. Earthquake countermeasure techniques.

<table>
<thead>
<tr>
<th>Earthquake countermeasure</th>
<th>Effect</th>
<th>Cost $c_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Countermeasure A</td>
<td>raises yield base shear coefficient $C_y$ from 0.1 to 0.3</td>
<td>1.4 million yen</td>
</tr>
<tr>
<td>seismic retrofitting to strengthening</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Countermeasure B</td>
<td>brings aged deterioration curve $R_m(t)$ back to initial value</td>
<td>1.4 million yen</td>
</tr>
<tr>
<td>seismic retrofitting to improving deformation performance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(d) There are three damage levels, complete, half and no destruction. The damage probability $P_{fi}$ and the loss $L_i$ of each damage level $i$ are shown in Table 2. The $R_m(0)$ of complete and half destruction are 0.1 and 0.05, respectively. In addition, if the house is completely destroyed, it assumes that the house is rebuilt. The loss of complete and half destruction are the asset value plus reconstruction cost $L_{(all)}$ and $L_{(all)}/3$, respectively. The asset value is written off for depreciation by the value of 50% every 25 years, and the new-built asset value $A_0$ is equal to initial construction cost. The reconstruction cost is equal to initial construction cost. The asset value $n$ years after from now $A_n$ is written as

$$ A_n = (1 - r)^n \cdot A_0 $$  \hspace{1cm} (11) 

where $r$ is depreciable rate.

Table 2. Damage probability and loss of each damage level.

<table>
<thead>
<tr>
<th>Damage level $i$</th>
<th>Damage probability $P_{fi}$</th>
<th>Loss $L_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete destruct-</td>
<td>$P_{f(all)}$</td>
<td>$P_{f(all)}$</td>
</tr>
<tr>
<td>Half destruct-</td>
<td>$P_{f(half)}$</td>
<td>$P_{f(half)} - P_{f(all)}$</td>
</tr>
<tr>
<td>No destruct-</td>
<td>$P_{f(no)}$</td>
<td>$1 - P_{f(half)}$</td>
</tr>
</tbody>
</table>

Figure 10. Seismic hazard in 30 years in Japan.

Figure 11. Seismic hazard curves over $t$ years.
4.2 Change in indexes according to timing of earthquake countermeasure

First of all, sensitivity analysis is applied to Kochi city in the case of changing timing of implementation $j_0$ of Countermeasure A. The sensitivity analysis result is shown in Figure 12. As shown on the Figure 12, the values of both indexes change significantly just after seismic countermeasures. It is because the seismic performance of the wooden house improves at the time of implementation of seismic countermeasures, and the ESL is decreased subsequently. Based on the presumption that strength of houses is not decreased every year for simplicity, yield base shear coefficient $C_y$ of the house is invariable regardless of timing of implementation. Hence, the LRI is also invariable regardless of the timing. In addition, since cost of earthquake countermeasures is same, the TCRI after countermeasures is invariable regardless of the timing likewise.

In the case of implementing at this time ($j_0=1$), although the LRI rises early, the TCRI goes negative value during present time to about 15 years later ($j_0=1-15$). On the other hand, in the case of implementing at 50 years later ($j_0=50$), although the TCRI remains positive value, the LRI keeps zero to 50 years later ($j_0=1-50$). At the case of $j_0=25$ or 50 years, the TCRI is positive value just after implementation, because decreasing of seismic loss by the countermeasure is bigger than the cost for the countermeasure. In order to achieve more loss reduction effect and be more cost-effective, the Countermeasure A should be implemented around the time of exchanging the TCRI negative to positive.

In this way, the indexes can consider a more cost-effective timing of implementing an earthquake countermeasure by comparing different timing of the countermeasures.

4.3 Change in index according to earthquake countermeasure techniques

Next, sensitivity analysis is applied to Osaka city in the case of changing earthquake countermeasure techniques implemented 25 years later ($j_0=25$). The result of sensitivity analysis which implements Countermeasure A and B respectively is shown in Figure 13. The LRI of Countermeasure A is higher than the LRI of Countermeasure B. Thus, Countermeasure A has a higher loss reduction effect than Countermeasure B. In addition, the TCRI of Countermeasure A is positive value. That means Countermeasure A is cost-effective. On the other hand, the TCRI of Countermeasure B is negative value almost in elapsed years. That means Countermeasure B is not cost-effective. Therefore, in this case, it can be said that Countermeasure A should be implemented rather than Countermeasure B.

In this way, the indexes can consider a more effective earthquake countermeasure technique by comparing different countermeasure techniques according to the indexes.

4.4 Change in index by location of earthquake countermeasure

Finally, sensitivity analysis is applied to five cities, Osaka city, Kyoto city, Nagoya city, Tsu city, and Kochi city, in the case of implementing Countermeasure A 25 years later ($j_0=25$). The result of sensitivity analysis at 50 years later ($u=50$) is shown in Figure 14. An especially big effect for LRI and TCRI is achieved in Nagoya, Tsu, and Kochi which are profoundly affected by Nankai and Tonankai earthquakes. On the other hand, a low effect for LRI and TCRI is achieved in Osaka, and Kyoto.

In this way, the effect of the loss reduction and cost-effectiveness are different according to locations even if it is the same countermeasures. Therefore, it leads to local earthquake countermeasure according to the indexes.
5 CONCLUSION

This paper presents a seismic risk evaluation method considering aged deterioration of wooden house and age softening of seismic hazard, and proposes indexes (Loss Reduction Index and Total Cost Reduction Index) based on the method. These indexes measure cost-effectiveness of earthquake countermeasure. Then, in order to assess the validity of the indexes, it implements sensitive analysis with the indexes. Consequently, it confirms that these proposal indexes can judge cost-effective timing and technique of earthquake countermeasure depending on location.

REFERENCES


