EVALUATION OF BUILDING DAMAGE BASED ON EQUIVALENT-PERFORMANCE RESPONSE SPECTRA

Y.Hayashi[1], A.Nii[2] and T.Morii[3]

[1] *Professor, Dept. of Architectural Engineering , Kyoto University, Kyoto, Japan*
[2] *Technology Center, Taisei Corp., Kanagawa, Japan*
[3] *Assistant Prof., Dept. of Architectural Engineering , Kyoto University, Kyoto, Japan*
Email: hayashi@archi.kyoto-u.ac.jp, ni-aik00@pub.taisei.co.jp, morii@archi.kyoto-u.ac.jp

ABSTRACT :

We have proposed an equivalent-performance response spectrum (EPRS), to evaluate response by earthquakes. The EPRS is the transformation of the restoring force characteristics of a SDOF system into the response spectra (RS) of ground motions. The EPRS enables you schematic interpretation of how the change in structural characteristics affects the maximum response, as well as how the change in ground motion characteristics affects the maximum response at the same time. First in this paper, the formulation of the EPRS for two-layered soil and wooden houses are introduced. Then, influence of the yield base-shear coefficient of houses on the damage is shown for illustration. Next, in order to demonstrate the validity of the EPRS, we simulate the damage of wooden houses during the recent major earthquakes in Japan by using the RS of observed ground motions. As a result of the simulation, the damage, which is related to the maximum response of houses, is successfully explained by the EPRS based on the wooden houses in the affected area. Finally, using an attenuation relationship for RS on engineering bedrock together with the proposed EPRS, we have demonstrated how the moment magnitude, minimum distance from fault plane and local site conditions affect the damage or loss of wooden houses.

KEYWORDS: Equivalent-performance response spectrum, response spectra, maximum response, damage probability, seismic loss, wooden houses

1. INTRODUCTION

The Capacity Spectrum Method (CSM) is well known as a performance-based seismic analysis technique. This method can be used for a variety of purposes (ATC (1996)). For example, the CSM is used for the rapid evaluation of a large inventory of buildings, design verification for new construction of individual buildings, evaluation of an existing structure to identify damage states, and correlation of damage states of buildings to various amplitudes of ground motion. In the CSM, the series of damped earthquake spectra and the capacity curve of a building are plotted in the spectral acceleration and spectral displacement plane. And the graphical intersection of the earthquake spectra and capacity curve indicates the response of the building to the earthquake motions.

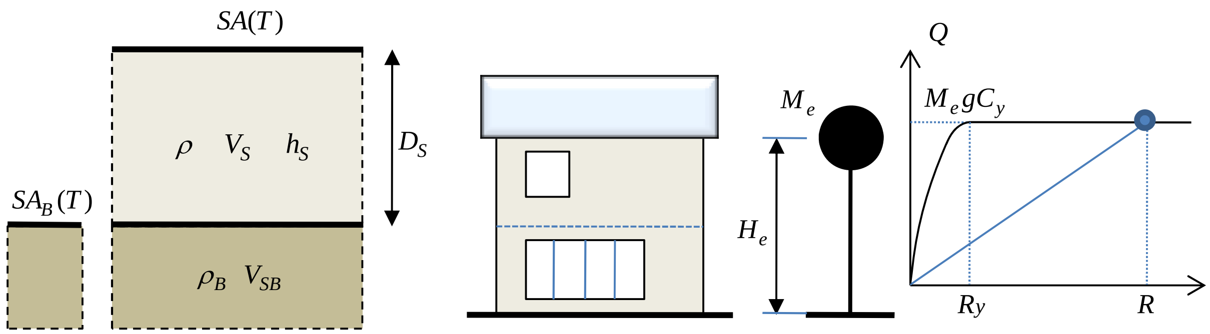
In this paper, we have proposed an equivalent-performance response spectrum (EPRS) method similar but alternative to the CSM. The EPRS is the transformation of the capacity curves of buildings into the equivalent response spectra of the same damping ratio as the response spectra (RS) of ground motions. The EPRS enables you schematic interpretation of how the change in structural characteristics affects the maximum response, as well as how the change in ground motion characteristics affects the maximum response at the same time. It is notable that many EPRS and many RS can be compared in a figure simultaneously.

In section 2, the formulation of the EPRS for two-layered soil and wooden houses is introduced. In section 3, in order to demonstrate the validity of the EPRS, we simulate the damage of wooden houses during the recent damage earthquakes in Japan by using the damage statistics and RS of ground motions. Finally, in section 4, using an attenuation relationship for RS on engineering bedrock together with the proposed EPRS, we have demonstrated how the moment magnitude, minimum distance from fault plane and local site conditions affect the damage or loss of wooden houses.

2. EQUIVALENT-PERFORMANCE RESPONSE SPECTRA

2.1. ESA(Equivalent Spectral Acceleration) of Two-layered Soil

To calculate the shear strain amplitude γ and soil-surface motion of the two-layered soil shown in Fig.1 (a), the surface -layer is modeled by a SDOF system (Morii et.al.(2003)).



(a) Two-layered soil (b) Wooden house

Figure 1 Analysis models of soil and wooden houses

Then, the equivalent spectral acceleration (ESA) as an example of EPRS for two-layered soil shown in Fig.1 (a) is formulated as follows. The effect of strain amplitude γ on shear modulus G and damping ratio h_S in the surface-layer soil are given as

$$G(\gamma) = G_0 / (1 + \gamma / \gamma_{0.5}) . \tag{2.1}$$

$$h_S(\gamma) = h_{\max}(1 - G(\gamma)/G_0) . \tag{2.2}$$

The G decrease and h_S increases when the shear strain amplitude γ increases. The natural period T_S of the soil is obtained using the thickness D_S and shear wave velocity $V_S(\gamma)$ of the surface layer by

$$T_S(\gamma) = 4D_S / V_S(\gamma) = T_{S0} / \sqrt{G(\gamma)/G_0} , \tag{2.3}$$

where $T_{S0} = T_S(0) = 4D_S / V_S(0)$ and $V_S(\gamma) = V_S(0)\sqrt{G(\gamma)/G_0}$. Then, the equivalent-performance spectral acceleration for a specified shear strain amplitude for the surface soil layer is given by

$$ESA_B(\gamma) = \frac{(2\pi / T_S(\gamma))^2 (\gamma D_S)}{F_h(h(\gamma))} , \tag{2.4}$$

if the following reduction factor F_h of response spectral acceleration is introduced,

$$F_h(h) = 1.5/(1 + 10h) . \tag{2.5}$$

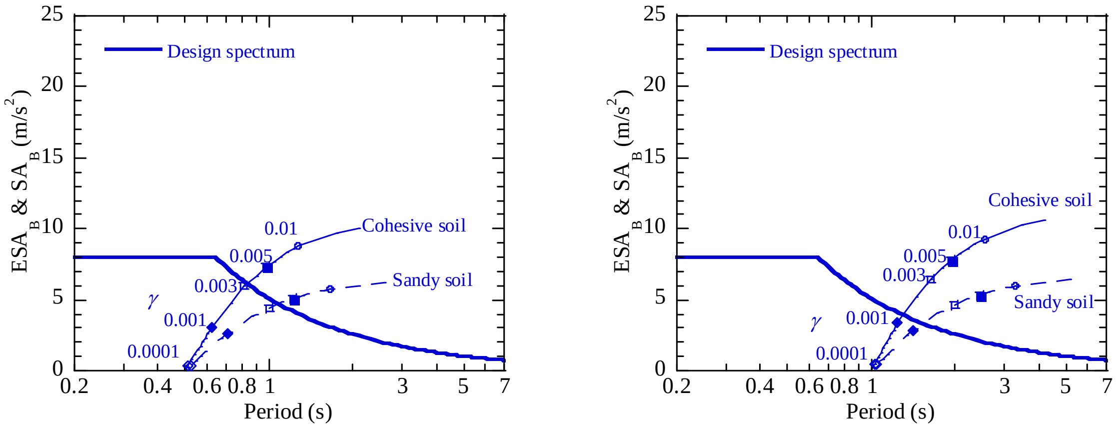
Since the amplification factor G_S of the two layered soil is defined by the ratio of surface motion to the engineering outcrop motion as,

$$G_S(T) = \frac{2}{\left|(1 + R_S)\exp(i2\pi D_S / TV_S) + (1 - R_S)\exp(-i2\pi D_S / TV_S)\right|} \tag{2.6}$$

where $R_S = \sqrt{1 + 2ih_S}\,\rho V_S / \rho_B V_{SB} = \sqrt{1 + 2ih_S}\,\alpha$ and $\alpha = \rho V_S / \rho_B V_{SB}$. The damping factor h in Eqns. 2.4 and 2.5 can be evaluated from the peak amplitude of amplification factor G_S.

$$h = 1/2G_S(T_S) = (0.5\pi h_S + \alpha)/2 \tag{2.7}$$

Equivalent Spectral acceleration $ESA_B(T_S)$ is plotted as a parameter of strain amplitude γ using Eqns. 2.3 and 2.4. Graphical intersection of the ESA for two-layered soil ESA_B and acceleration response spectra on the engineering outcrop motion $SA_B(T)$ gives us the response of the surface soil layer. Thus, the natural period T_S and strain amplitude γ are calculated numerically, but you can easily understand them from graphical intersection as shown in Figs. 2 (a) and (b). In these figures, we set $\gamma_{0.5}$=0.18%, $h_{\max}$=0.17 for cohesive soil or $\gamma_{0.5}$=0.10%, $h_{\max}$=0.21 for sandy soil, and $\rho = \rho_B$, V_{SB}=400m/s for demonstration. The thick line in Fig. 2 shows the design spectral acceleration SA_B defined on the engineering bedrock in Japan.



(a) $\alpha(0)$=0.5, $T_S(0)$=1.0s (b) $\alpha(0)$=0.3, $T_S(0)$=0.5s

Figure 2 ESA of two layered soil and design SA on the engineering bedrock

Then, the spectral acceleration on the soil surface $SA(T)$ can be obtained by the following equation.

$$SA(T) = G_s(T)SA_B(T) \tag{2.8}$$

2.2. ESA of Wooden houses

To calculate the maximum drift angle R of wooden houses, houses are modeled by the SDOF system as shown in Fig. (1). If the restoring force-displacement relation is assumed to be bilinear, equivalent natural period T_e for the maximum drift angle R larger than yield deformation angle R_y (=1/100) can be expressed as follows using the equivalent mass ratio μ and equivalent height H_e, yield base shear coefficient C_y.

$$T_e(R,C_y)=2\pi\sqrt{\mu RH_e/C_y g} \qquad (R > R_y) \tag{2.9a}$$

Equivalent natural period T_e for R smaller than R_y can be determined as follows based on the results of earthquake observations for three traditional wooden houses in Japan (Hayashi et. al. (2005)).

$$T_e(R,C_y)=2\pi\sqrt{\{(1+9(R/R_y)^{0.7})/10\}\mu R_y H_e/C_y g} \qquad (R \le R_y). \tag{2.9b}$$

If the damping factor h_e for R is given by

$$h_e(R) = 0.05 + 0.2(1-1/(\max(\sqrt{R/R_y},1)), \tag{2.10}$$

the equivalent spectral acceleration ESA_S of a wooden house can be expressed as

$$ESA_S(R,C_y) = \frac{\left(2\pi/T_e(R,C_y)\right)^2 (RH_e)}{F_h(h_e(R))}. \tag{2.11}$$

The response of the house for the soil-surface motion corresponds to the graphical intersection of the ESA in Eq. (11) and SA in Eq. (8). The equivalent natural period T_e is obtained by convergent calculation, but you can easily understand it graphically. Two thick lines in Fig. 3 show the design acceleration response spectra SA in Japan for two types of soil condition. Three thin lines in Fig. 3 show the ESA_S for wooden houses of C_y=0.1, 0.3, 0.5. The μ=0.9 and H_e =4.5m is set for the calculation. The graphical intersection of a thick line and a thin line is the response of the house to the design motions. Using the equivalent performance spectra and response spectra, you can easily understand how the strength of houses C_y and input motion characteristics influence the response R simultaneously.

By the way, fragility functions of damage state i, P_{fi} with the maximum drift angle R of a wooden house can be given by

$$P_{fi}(R) = \Phi((\ln(R) - \ln(R_{mi}))/\zeta_i), \tag{2.12}$$

where Φ is the cumulative distribution function (CDF) of the standard normal distribution, and $\ln(R_{mi})$ and ζ_i are the average and standard deviation of $\ln(R)$, respectively. The parameters i=1, 2, 3 are partially destroyed, half destroyed, and completely destroyed, respectively. Furthermore, if seismic loss normalized by the initial cost

C_i at damage state i, the normalized expected loss L can be given by

$$L(R) = C_1(P_{f1}(R) - P_{f2}(R)) + C_2(P_{f2}(R) - P_{f3}(R)) + C_3 P_{f3}(R)\,. \tag{2.13}$$

If we set ζ_i=0.4, R_{m1}=0.025, R_{m2}=0.05, R_{m3}=0.1, C_1=0.2, C_2=0.5, C_3=1.0 in this paper, the fragility functions and expected loss function can be plotted as shown in Fig.4. Using Eqns. 2.12 and 2.13, the equivalent performance spectra can be plotted by the parameter of damage probability or expected loss instead of R. Then, you can easily understand how the strength of houses C_y and input motion characteristics influence the damage probability or expected loss.

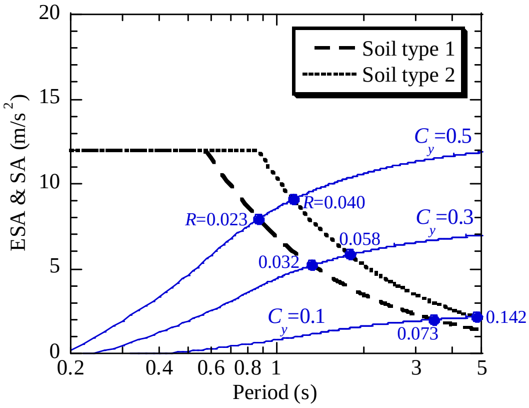


Figure 3 Design spectra in Japan and ESA

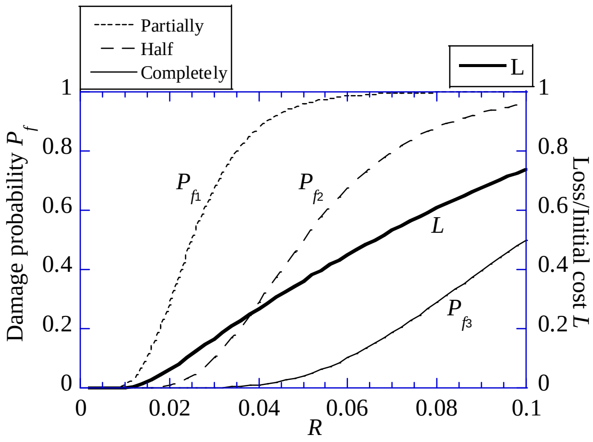


Figure 4 Damage probability and expected loss with R

3. COMPARISON WITH OBSERVED GROUND MOTIONS

In this section, the proposed EPRS in section 2 is applied to explain the wooden houses damage during recent earthquakes in Japan. Table 1 shows the list of earthquakes. Ground motions observed near field of epicenter in each earthquake are used in this analysis.

The SA of observed ground motions and ESA of wooden houses are shown in Fig. 5. In this study, the yield base shear coefficient C_y is set at 0.1, 0.3, 0.5 and 0.7 to include any situations. The graphical intersection of a SA and an ESA gives the maximum drift angle R of wooden house. In Figs. 5, damage of wooden houses are classified into 4 types, (a) No damage or partially destroyed, (b) Partially destroyed or completely destroyed, (c) Many houses are completely destroyed and (d) Many houses collapsed. Typical wooden house damage is shown in Photo 1.

The followings can be pointed out from each figure.

(a) No damage or partially destroyed : This type of damage can be seen in the 2001 Geiyo earthquake and 2008 Iwate-Miyagi earthquake (IWTH26). The wooden houses damage is fall of roofs, cracks of exterior walls, etc. The R is much smaller than 0.02 rad. regardless of C_y although response spectrum is very high in the short period range of 0.2 to 0.4 second.

(b) Partially destroyed or completely destroyed: This type can be seen in the 2007 Noto earthquake. Wooden houses damage is polarized, partially destroyed or completely destroyed. In the case of C_y being less than 0.1, R is larger than 0.1 rad. On the other hand, for higher C_y, R is much smaller than 0.01rad. Therefore, the damage of wooden houses strongly depends on C_y values.

(c) Many houses are completely destroyed: This type can be seen in the 1995 Kobe earthquake (JMA Kobe), 2000 Tottori earthquake, 2004 and Chuetsu earthquake (NIG019). Although there were few collapsed houses, structural damage such as large cracks of mud walls and inclination of columns can be seen in many wooden houses. The R is about 0.05rad for all C_y values. As for this type of ground motins, the damage of wooden houses cannot be mitigated by increasing the strength of wooden houses.

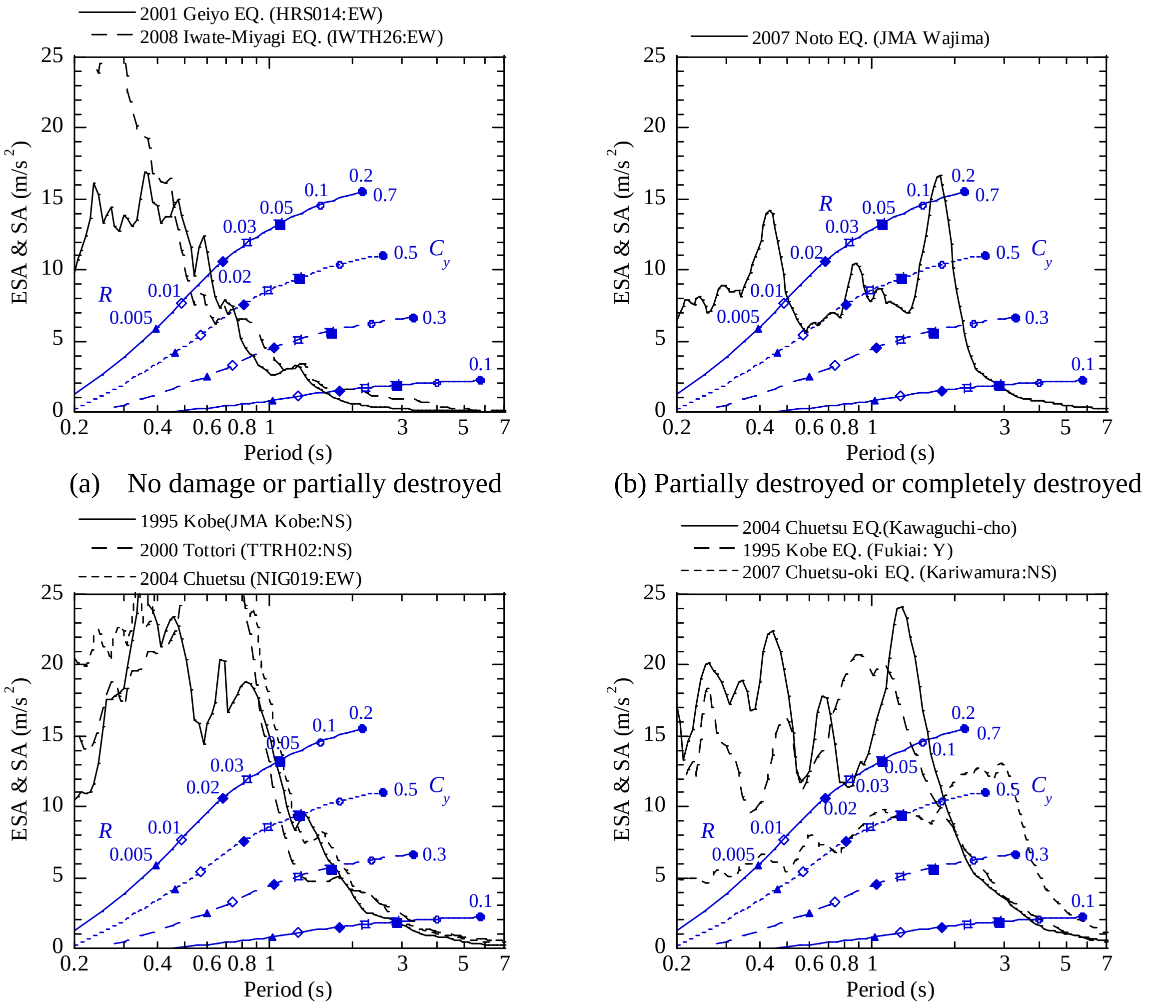
(d) Many houses collapsed: This type can be seen in the 1995 Kobe earthquake (Fukiai), 2004 Chuetu earthquake (Kawaguchi) and 2007 Chuetsu-oki earthquake (Kariwa). The R is larger than 0.1rad regardless of C_y values. Therefore, collapsing does not depend on C_y values, but on deformation capacity of wooden houses.

As mentioned above, the wooden houses damage is successfully explained by using the proposed method. Additionally, in the case of strong ground motions with predominant period in the range of 1 to 3 seconds, wooden houses damage cannot be mitigated by increasing C_y. Therefore, it is important to consider not only the strength of wooden houses but also deformation capacity to mitigate damage states of wooden houses.

Table 1 Observed ground motions in Japan

Date	Earthquake	Station	Comp.	Mw	D (km)	PGA (Gal)	PGV (cm/s)	Major damage state
1995.01.17	1995 Hyougo-ken Nanbu, Kobe, EQ.	Fukiai	Y	6.9	10	802	129	3-4
1995.01.17	1995 Hyougo-ken Nanbu, Kobe, EQ.	JMA Kobe	NS	6.9	10	818	86	3
2000.10.06	2000 Western Tottori Prefecture EQ.	TTRH02	NS	6.8	11	927	112	3
2001.03.24	2001, Geiyo EQ.	HRS014	EW	6.7	51	441	32	1
2004.10.23	2004 Niigata-ken Chuetsu EQ.	NIG019	EW	6.6	13	1309	134	3
2004.10.23	2004 Niigata-ken Chuetsu EQ.	Kawaguchi	EW	6.6	13	1666	134	3-4
2007.03.25	2007 Noto Peninsula EQ	JMA Wajima	EW	6.7	11	464	97	1-4
2007.07.16	The Niigataken Chuetsu-oki EQ. in 2007	Kariwa	NS	6.7	8	461	122	4
2008.06.14	The Iwate-Miyagi Nairiku EQ. in 2008	IWTH26	EW	6.9	8	1056	43	0

* 0: No damage, 1:Partially destroyed, 2: Half destroyed, 3: Completely destroyed, 4: Collapse



(a) No damage or partially destroyed
(b) Partially destroyed or completely destroyed
(c) Many houses are completely destroyed
(d) Many houses collapsed

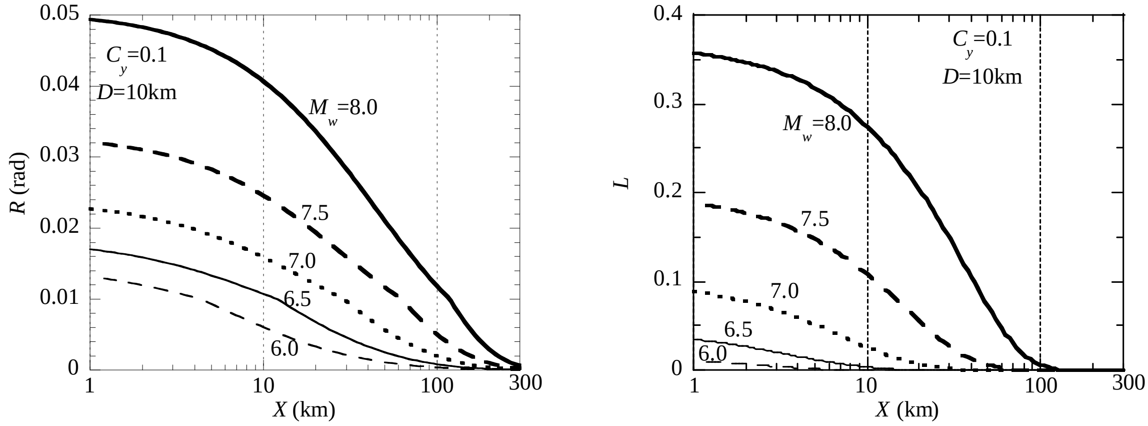
Figure 5 ESA of wooden houses and SA of observed ground motions

HRS014(2001 Geiyo EQ.) JMA Wajima (2007 Noto EQ.) Kawaguchi (2004 Chuetsu EQ.)

Photo 1 Typical wooden house damage around observation stations.

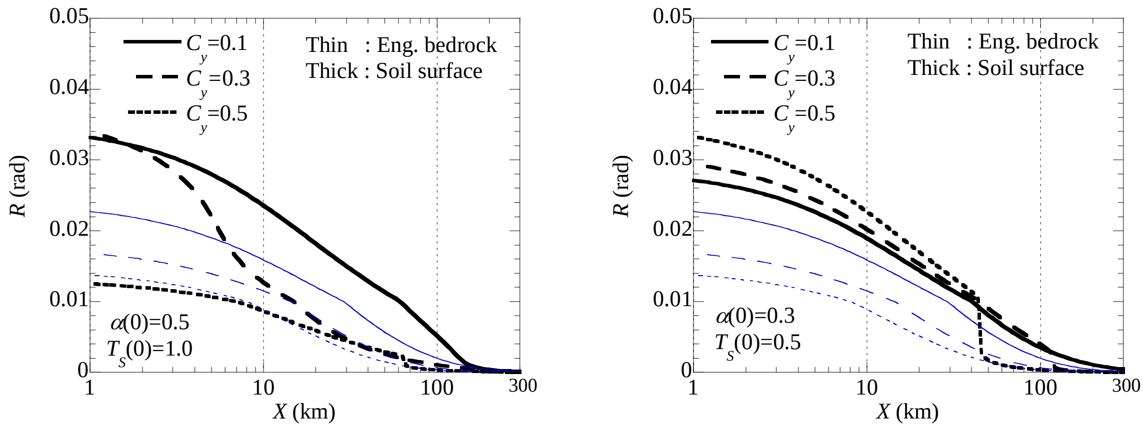
4. ATTENUATION OF WOODEN HOUSE RESPONSES

In this section, relationship of the maximum drift angle *R* and expected loss *L* of wooden houses to the minimum distance from fault plane *X* is studied using the attenuation relationship of response spectra. The acceleration response spectra on engineering outcrop SA_B is calculated by using the attenuation relationship (Uchiyama et.al. (2006)) which is developed based on strong motion data from earthquakes occurred in and around Japan. To determine the SA_B, required parameters are moment magnitude M_w, minimum distance from fault plane *X* and focal depth *D*. Though this relationship has characteristics of considering the effect of focal depth *D*, *D* is fixed at 10km in this study to represent shallow local earthquakes. By finding each intersection point of *SA* at each distance *X* and proposed *ESA* of wooden houses, maximum drift angle *R* of wooden house for each *X* is obtained. Then, the expected loss *L* is calculated using Eqn. 2.13. By plotting *R* or corresponding *L* versus *X*, the attenuation relationship of *R* or *L* of wooden houses are illustrated as shown in Figs. 6(a) and (b), respectively. Figure 6 shows attenuation relationship for wooden house of C_y=0.1 varying moment magnitude M_w=6.0, 6.5, 7.0, 7.5, 8.0. It is calculated under the assumption that there is no amplification at surface soil layer. To evaluate the effect of surface soil condition, response spectra is amplified by amplification factor G_S using Eqn. 2.6. Example of *SA* on soil surface and ESA of wooden house is shown by dashed lines and solid lines respectively in Fig. 9. Parameters are set M_w=7.0 and *X*=1.0km (dashed line) or 10.0km (dotted line) for calculation of *SA*, and C_y = 0.1, 0.3, 0.5, for calculation of ESA. Figure 7(a) is for surface soil condition of $T_S(0)$=1.0 and $\alpha(0)$=0.5, and Fig. 7(b) is for $T_S(0)$=0.5 and $\alpha(0)$=0.3. Thick lines in Fig. 7 show attenuation relationship of *R* considering the surface soil condition, and thin lines show for the cases engineering outcrop motion subjected. For the case of without considering the amplification at surface-layer (thin lines in Fig.7), *R* becomes smaller according as the C_y increases, and *R* decreases monotonically with *X*. On the other hand, for the soil condition of $T_S(0)$=0.5 and $\alpha(0)$=0.3, (thick lines in Fig. 7(b)), *R* for C_y =0.5 is larger than that for C_y =0.1 when *X* is shorter than 50km. And for the values of *X* longer than 50km, *R* for C_y=0.5 becomes smaller. This surface soil condition can be understood by Figs. 9(a) and (b). These results suggest the importance of considering the surface soil condition.
The calculated response *R* shown in this section is smaller than the results shown in section 3. It can be considered as possible reasons that the amplification characteristics of ground motions due to deep sedimentary layer, basin edge effects, and directivity effects in the near-fault regions are not considered in the calculation of SA.



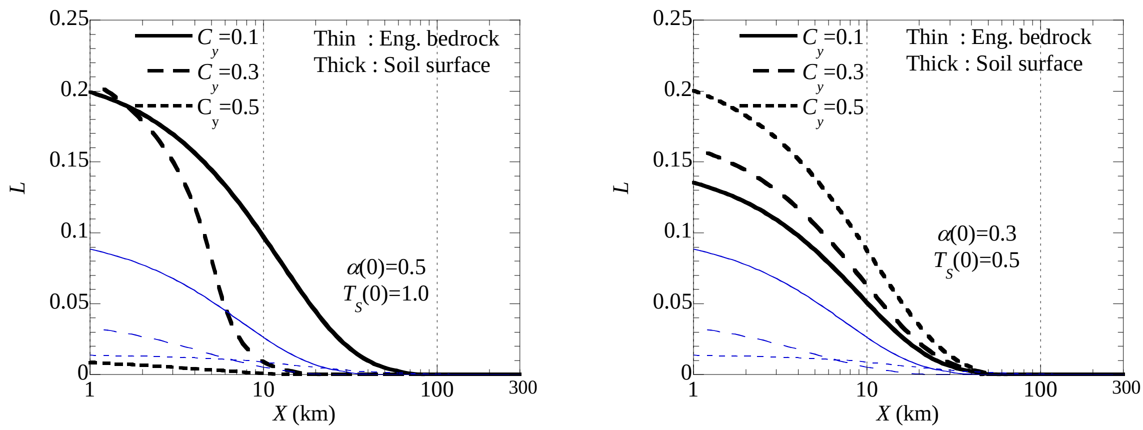
(a) Maximum drift angle (b) Expected loss

Figure 6 Attenuation of maximum drift angle and expected loss (effect of M_w)



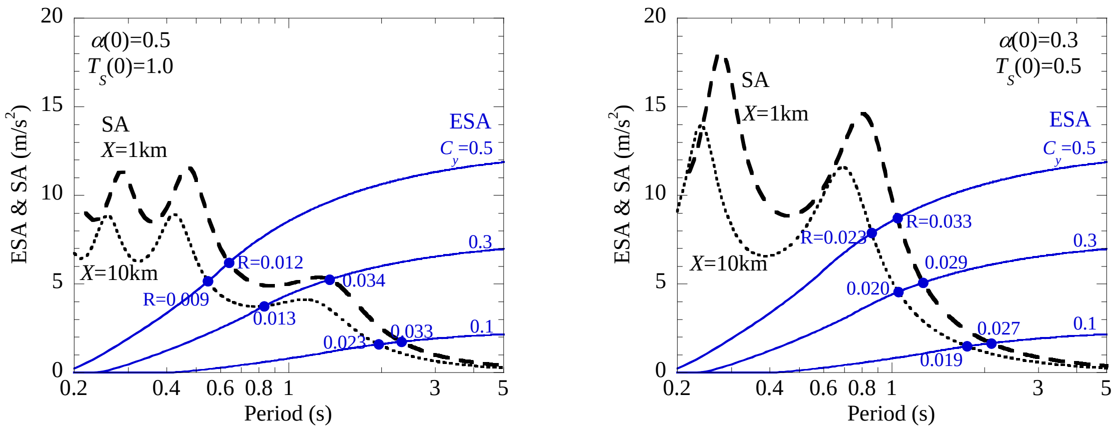
(a) $\alpha(0)$=0.5, $T_S(0)$=1.0s (b) $\alpha(0)$=0.3, $T_S(0)$=0.5s

Figure 7 Attenuation of maximum drift angle (Effect of soil condition)



(a) $\alpha(0)$=0.5, $T_S(0)$=1.0s (b) $\alpha(0)$=0.3, $T_S(0)$=0.5s

Figure 8 Attenuation of expected loss (Effect of soil condition)



(a) $\alpha(0)$=0.5, $T_S(0)$=1.0s (b) $\alpha(0)$=0.3, $T_S(0)$=0.5s

Figure 9 Comparison of ESA and SA at the different site conditions

5. CONCLUSION

We have proposed an equivalent-performance response spectrum (EPRS) to evaluate the response during earthquakes. First, we formulate the equivalent spectral acceleration (ESA) for two layered soil and wooden houses as examples of the EPRS. Then, in order to demonstrate the validity of the EPRS, we explain the damage of wooden houses during the recent major earthquakes in Japan using the ESA. Finally, using an attenuation relationship for SA on the engineering bedrock together with the ESA, the attenuation relationship of the maximum response and expected loss for wooden houses are presented. As results, following conclusions have been drawn.

1) The proposed EPRS enables you schematic interpretation of how the change in structural characteristics affects the maximum response, as well as how the change in ground motion characteristics affects the maximum response.
2) The recent wooden house damage can be successfully explained by using the EPRS.
3) The attenuation relationship of the maximum response and expected loss enable us to understand how the moment magnitude, minimum distance from fault plane and local site conditions affect the damage.

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