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PREDICTION OF DAMAGE RATE OF BUILDING GROUPS IN URBAN AREAS BY STRONG EARTHQUAKES

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SUMMARY

Review of previous researches is made on the damage rate of buildings by strong earthquakes and the vulnerability curves based on the data of past earthquake damages. A mathematical model of building damage rate by earthquakes considering the probability distribution both for the earthquake resistance capacity and the earthquake force is discussed and theoretical vulnerability curves are shown in terms of peak ground acceleration and seismic intensity. Finally, a study is made on the vulnerability curves of wooden buildings based on the information on the observed damage rate and the estimated ground motion intensity of the most severely shaken area in the 1995 Hyogo-ken Nanbu earthquake.

INTRODUCTION

Prediction of earthquake damage to building groups is essential for the evaluation of urban seismic risk by strong earthquakes. The extent of earthquake damage to a group of buildings is usually expressed by the damage rate which is the fraction of the number of buildings that suffered damage above a certain level to the total number of buildings in an area. The damage rate is defined for a building group of a certain structural type in a certain area in which the ground motion intensity is considered to be nearly the same.

The damage rate of building groups is conveniently utilized to estimate various kinds of urban damage such as the number of casualties, the number of refugees, the number of fires and so on in the work of urban seismic risk prediction. The relation between the damage rate and the estimated level of ground motion intensity is called vulnerability curve or vulnerability function. A number of vulnerability curves for various building groups have been obtained from the damage data of past strong earthquakes.

Information on the damage rate of buildings can be generalized by considering the mathematical model which takes account of the factors affecting the building damage. A probabilistic model for evaluating the damage rate of building groups is discussed in this paper. The model assumes the probability distributions both for the building resistance capacity and the earthquake force exerted on buildings and evaluates the damage rate of a group of buildings by the reliability theory. Theoretical vulnerability curves can be obtained from the probabilistic model, which can be compared with the empirical curves obtained from the actual data of building damage rate in strong earthquakes.

PREVIOUS WORKS

Many studies have been made on the damage rate of buildings in Japan. Mononobe was the first to investigatethe relation between the damage rate of collapsed wooden houses and the ground motion intensity estimated from the overturning of tomb stones which is equivalent to ground seismic coefficient [Mononobe, 1933]. **Fig. 1**

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shows the relations obtained from the damage data of several large earthquakes in Japan and theoretical curves expressed by normal probability distribution function (rewritten after his original figure).

Shiga discussed the damage rate of reinforced concrete buildings based on his research on the earthquake resistance capacity of existing reinforced concrete buildings [Shiga, 1976]. He derived a simple formula to estimate roughly the resistance capacity of low-rise reinforced concrete buildings using the amount of column areas and wall areas through the analysis of damaged as well as undamaged buildings in the 1968 Tokachi-oki earthquake and the 1978 Miyagiken-oki earthquake. He estimated the probability distribution of the earthquake resistance capacity of existing low-rise reinforced concrete buildings and modeled the probability distribution by Gamma distribution, based on which he gave the relation between the damage rate of reinforced concrete buildings and the ground motion intensity [Shiga, 1977].

Shibata presented a probabilistic model for the damage rate of building groups by assuming that both the resistance capacity of buildings and the earthquake force exerted on buildings are random variables having the probability distribution of log-normal type [Shibata, 1980]. The theoretical relation between the damage rate and the ground motion intensity was given based on the reliability theory. The damage rate of low-rise reinforced concrete buildings in Sendai area observed in the 1978 Miyagiken-oki earthquake was investigated and compared with the theoretical result using this probability model [Shibata, 1984].

Okada studied the expression of vulnerability function for wooden buildings and other urban disasters in terms of intensity scale having the form of normal probability distribution[Okada, 1990].

Miyakoshi et al. made a detailed study on the vulnerability curves of wooden houses and reinforced concrete buildings in terms of the maximum ground velocity based on the data of building damage in the 1995 Hyogo-ken Nanbu earthquake [Miyakoshi et al., 1997].

PROBABILISTIC MODEL OF DAMAGE RATE

A probability model is discussed for the damage rate evaluation of a group of buildings in strong earthquake, which can reasonably reflect the characteristics of building resistance and earthquake force [Shibata, 1997].

It is assumed that the earthquake resistance capacity of a group of buildings in an area and the earthquake force exerted on buildings are both expressed by random variables and that the damage rate of a group of buildings by earthquake is the probability that the earthquake force exceeds the effective earthquake resistance capacity. We assume that the effective earthquake resistant capacity is expressed by the product of the building strength and the coefficient corresponding to the damage level, where the building strength is the random variable.

Denoting the earthquake force and the building strength by the random variables S and R, respectively, and the coefficient corresponding to the damage level j by d_j, the damage rate of a group of buildings P_j is defined as the probability that the earthquake force S exceeds the effective earthquake resistance capacity $d_j R$, (**Fig. 2**) as shown in the following.

$$P_j = P_r\left[d_j R \leq S\right] \tag{1}$$

It is assumed here that the building strength R is the random variable having the log-normal probability distribution with mean $\bullet_R$. and standard deviation $\bullet_R$.

For ductile structures, we can assume that the coefficient for heavy damage level d_h is expressed as follows by considering the energy conservation rule,

$$d_h = \sqrt{2\mu - 1} \tag{2}$$

where •is the ductility factor corresponding to heavy damage.

Fig. 3 shows conceptually the effective earthquake resistance capacity for small damage $d_s R$, medium damage $d_m R$ and heavy damage $d_h R$.

The earthquake force S is expressed by the product of the peak ground acceleration A and the building response amplification factor c.

$$S = cA \tag{3}$$

The peak ground acceleration A is assumed to be the random variable having the log-normal probability distribution with mean$\bullet_A$ and standard deviation$\bullet_A$. The response factor c is essentially related to the natural period of buildings and the characteristics of earthquake motion. The variation of response factor is tentatively assumed to be included in the variation of the peak ground acceleration A, and c is assumed to be constant here. The ground motion intensity can also be expressed by the seismic intensity I which is assumed to berelated to the peak ground acceleration A by the following relation.

$$A = a_1 e^{a_2 I} \tag{4}$$

$$I = \frac{\ln A - \ln a_1}{a_2} \tag{5}$$

where a_1=0.45, a_2=0.5ln10=1.15

As the peak ground acceleration A is assumed to be log-normal, the seismic intensity I becomes the random variable having the normal probability distribution.

The damage rate P_j of a building group for the damage level j is expressed either by A or by I as follows.

$$P_j = \Pr\left[d_j R \le S\right] = \Pr\left[\frac{d_j R}{c} \le A\right] = \Pr\left[R_{Aj} \le A\right] \tag{6}$$

$$P_j = \Pr\left[\ln(d_j R) \le \ln S\right] = \Pr\left[\frac{1}{a_2}\ln\frac{d_j R}{c a_1} \le I\right] = \Pr\left[R_{Ij} \le I\right] \tag{7}$$

In the above equations, R_{Aj} and R_{Ij} are the effective earthquake resistance for damage level j as expressed by the unit of ground acceleration and seismic intensity, respectively. The mean and the standard deviation of $R_{\mathrm{A}j}$ and R_{Ij} are expressed as follows.

$$\mu_{RAj} = \frac{d_j \mu_R}{c} \tag{8}$$

$$\mu_{RIj} = \frac{1}{a_2}\ln\frac{d_j \mu_R}{c a_1} \tag{9}$$

$$\sigma_{RAj} = V_R \mu_{Aj} \tag{10}$$

$$\sigma_{RIj} = \frac{V_R}{a_2} \tag{11}$$

where V_R is the coefficient of variation of building resistance R.

Finally, the damage rate of a building group P_j is expressed either by the mean of peak ground acceleration $\bullet_A$ or by the mean seismic intensity $\bullet_I$ as follows by using the reliability theory.

For the mean peak ground acceleration,

$$P_j = \Phi\left[\frac{\ln(\mu_A / \mu_{RAj})}{\sqrt{{V_R}^2 + {V_A}^2}}\right] \tag{12}$$

For the mean seismic intensity,

$$P_j = \Phi\left[\frac{\mu_I - \mu_{RIj}}{\sqrt{V_R{}^2 + V_A{}^2} \,/\, a_2}\right] \tag{13}$$

where • is the standard normal distribution function and •$_I$ is expressed as follows.

$$\mu_I = \frac{1}{a_2}\ln\frac{\mu_A}{a_1} \tag{14}$$

The vulnerability curve is the damage rate expressed as the function of the ground motion intensity. **Figs. 4** and **5** show examples of vulnerability curves expressed in terms of the mean peak ground acceleration and the mean seismic intensity for reinforce concrete building groups in Japan. The coefficient for damage level d_j is assumed to be 1.0 considering medium damage d_m. The mean values of building strength •$_R$ for 2, 3 and 6 storied reinforced concrete building groups are assumed to be 1.73G, 1.19G and 0.94G, respectively, and the coefficients of variation for building strength V_R is assumed to be 0.46 for all building groups, according to the study on the probabilistic nature of the strength of existing low-rise reinforced concrete buildings[Onose, 1984]. The coefficient of variation for the earthquake force V_A, is tentatively assumed to be 0.4. The coefficient of variation for earthquake force is very difficult to estimate, because it includes various factors such as the variation in the maximum peak ground motion at bedrock in a certain period, the variation of the effect of surface ground and deep ground structure, the variation in the amplification factor of building response and so on.

It is noted that the variation of building strength and earthquake force, V_R and V_A , are mixed into one variable in Eqs. 12 and 13, which means that it is difficult to estimate the variation of building strength and earthquake force separately only from the information of empirical vulnerability curves.

DAMAGE RATE IN 1995 HYOGO-KEN NANBU EARTHQUAKE

The relation between the damage rate of buildings and the ground motion intensity is discussed using the data of the most severely shaken area in the 1995 Hyogo-ken Nanbu earthquake.

Severely damaged areas by the Hyogo-ken Nanbu earthquake were located in a narrow belt along the fault extending from the Awaji Island to Takarazuka city, which includes Kobe, Ashiya and Nishinomiya cities. The intensity of ground motion in the “damage belt” was very strong because of near field earthquake. Moreover, it is considered strongly affected by the irregular ground structure underlying those cities.

Motosaka et al. made an analytical investigation on the spatial variation of ground motion along the line perpendicular to the fault considering the irregular deep underground structure as well as the surface ground condition and using the strong motion record at Kobe University [Motosaka and Nagano, 1996]. **Fig. 6** shows the variation of peak ground acceleration along the line perpendicular to the fault. From this figure we see that the surface ground motion is very high at the distance of about 1 km from the structural discontinuity in deep ground and this fact can explain well the “damage belt” of this earthquake [Motasaka and Nagano, 1996]. In **Fig. 6**, FN means fault normal and SUOG means surface of upper part of Osaka layer group.

The spatial distribution of estimated ground motion intensity by Motosaka agrees well with the result of investigation on the spatial distribution of damage rate of buildings along the line perpendicular to the fault as shown in **Fig. 7** [Ono et al., 1995]. It is noted that the majority of this data is for wooden buildings though the data includes some of reinforced concrete buildings. The relation between the damage rate and the ground motion intensity is obtained from the above data as shown in **Fig. 8** [Motasaka et al., 1998]. The smooth curve shows the vulnerability curve obtained by fitting the log-normal probability distribution.

The information on the damage rate of wooden buildings is also available from the extensive research report by Architectural Institute of Japan [Architectural Institute of Japan, 1998].

Comparison of old and new vulnerability curves for wooden buildings by strong earthquakes in Japan are shown in **Fig. 9** (1891 Nobi eq., 1914 Akita Senpoku eq., 1923 Kanto eq., 1946 Nankai eq., 1948 Hukui eq., 1978 Miyagiken-oki eq., 1995 Hyogo-ken Nanbu eq.)[Motasaka et al., 1998]. We see from this figure that the strength of wooden buildings has been increased with time. Also, we see that the apparent dispersion of damage rate is larger for recent earthquakes because the accuracy of the information both on ground motion intensity and damage rate has been improved and more detailed data on damage rate have become available.

CONCLUSIONS

The damage rate of building groups by strong earthquakes is discussed from empirical and theoretical points of view. A probabilistic model for evaluating the damage rate of a group of buildings by earthquake is presented and the theoretical vulnerability curves are given in terms of the mean peak ground acceleration and the mean seismic intensity. A study is made on the damage rate of wooden buildings in the 1995 Hyogo-ken Nanbu earthquake. The vulnerability curves of old and new Japanese wooden buildings are investigated.

Research on the vulnerability curves for building groups of various structural types will be useful for predicting the damage to urban facilities/functions in case of future earthquakes and for considering the emergency measures after big earthquake.

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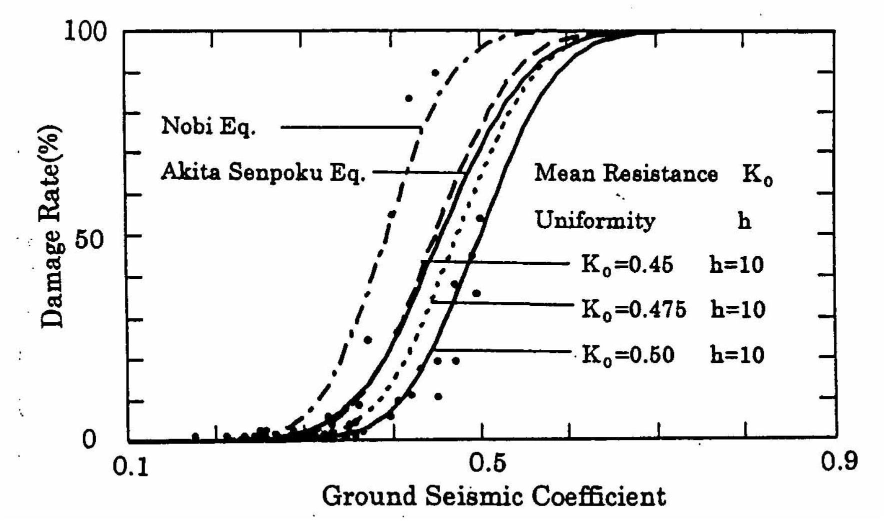

Figure 1: Damage Rate of Wooden Buildings by Earthquakes (after Mononobe, 1933)

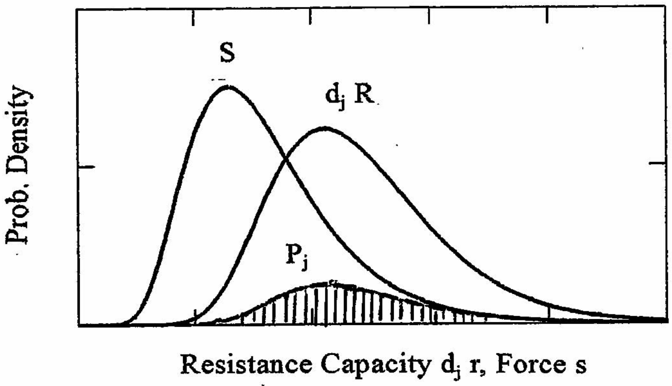

Figure 2: Probability Distribution of Resistance Capacity and Earthquake Force

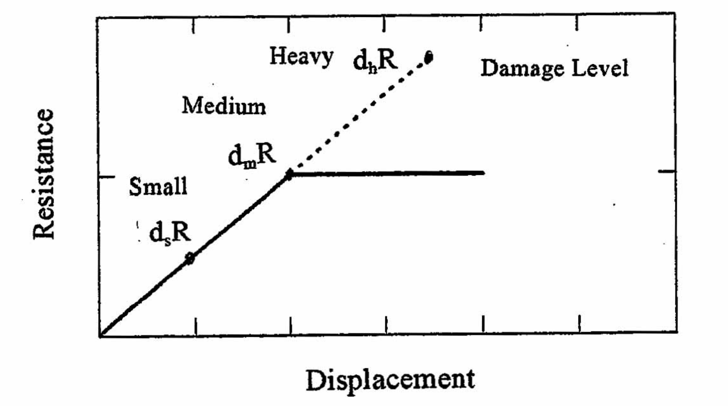

Figure 3: Effective Earthquake Resistance Capacity

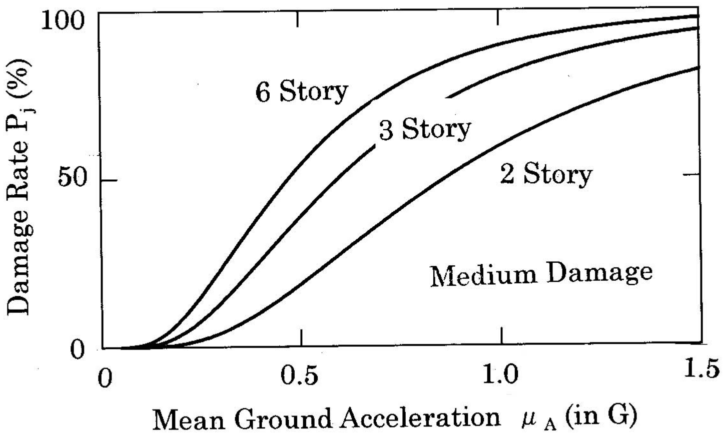

Figure 4: Vulnerability Curve in Terms of Peak Ground Acceleration in G (gravity acceleration)

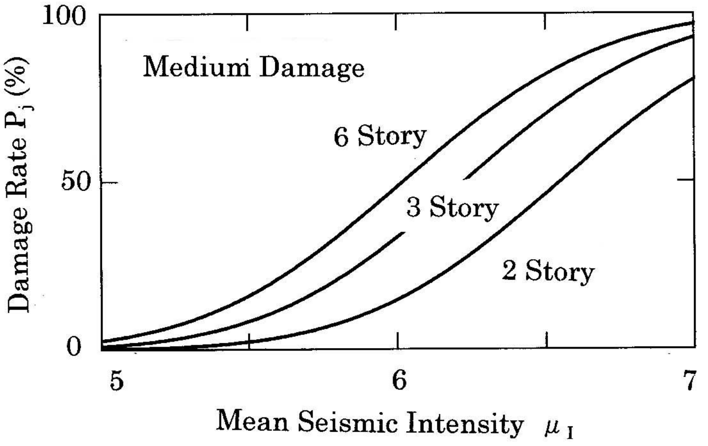

Figure 5: Vulnerability Curve in Terms of Seismic Intensity

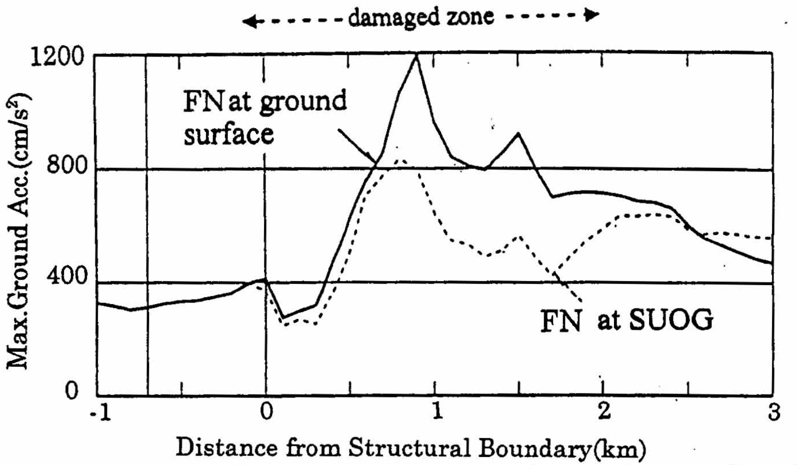

Figure 6: Estimated Distribution of Peak Ground Acceleration along Line Perpendicular to Fault

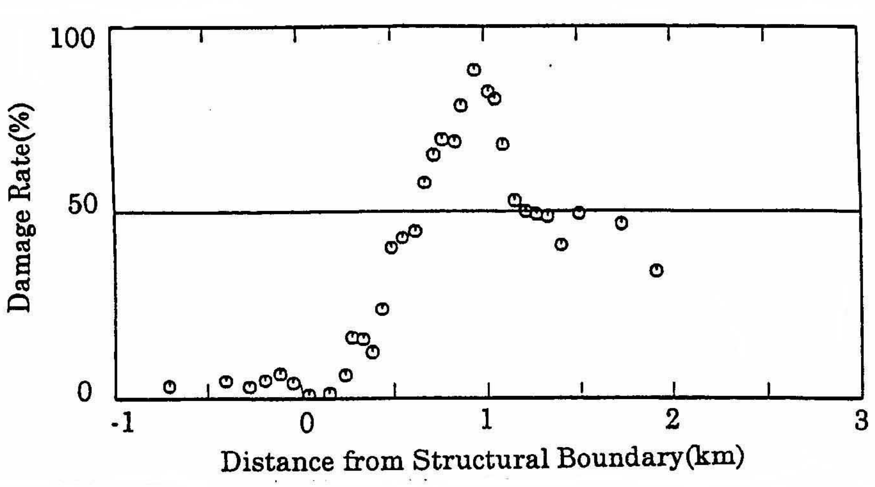

Figure 7: Distribution of Damage Rate of Buildings in Hyogo-ken Nanbu Eq. (after Ono, 1995)

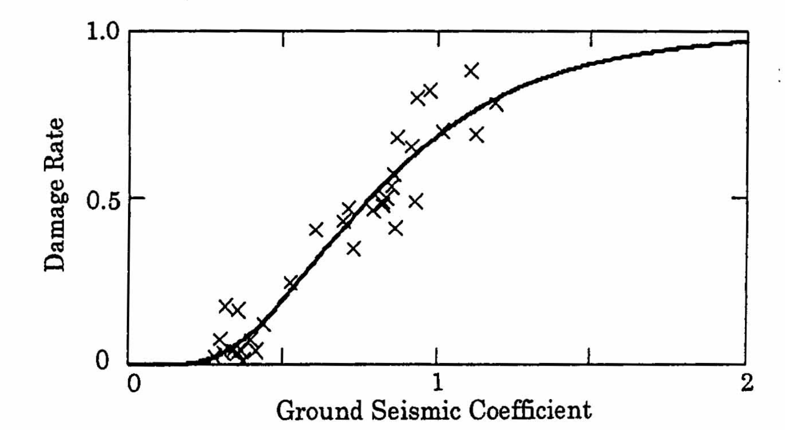

Figure 8: Estimated Vulnerability Curve of Buildings by Hyogo-ken Nanbu Earthquake

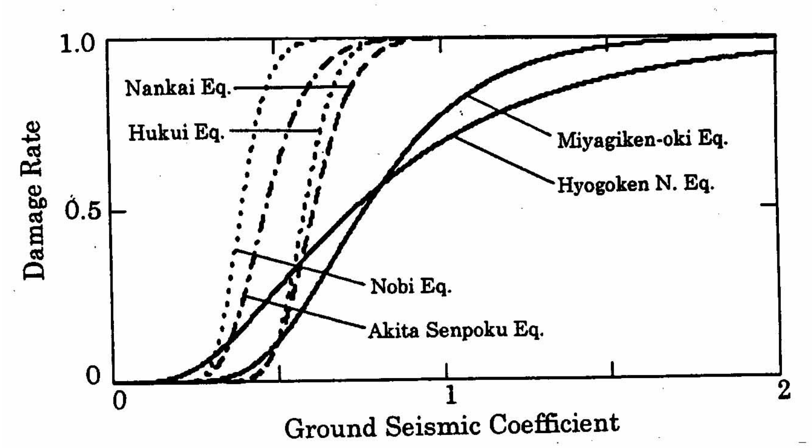

Figure 9: Comparison of Vulnerability Curves for Wooden Buildings by Various Earthquakes