PREDICTION OF THE PROBABILITY OF EARTHQUAKE DAMAGE TO REINFORCED CONCRETE BUILDING GROUPS IN A CITY

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SUMMARY

This paper presents a method for predicting the probability of earthquake damage to a group of buildings in a city for a given period of time considering the probability distributions of both the earthquake force and the seismic resistance capacity of buildings. The probability distribution of the resistance capacity is based on the study of existing buildings. The method is applied to hypothetical models of building groups located in Sendai city and also to a case of actual damage in 1978 Miyagi-ken-oki earthquake.

INTRODUCTION

It is considered that the variation in the ultimate seismic resistance capacity of existing buildings as well as the variation in the level and the characteristics of ground motion is an important factor affecting the extent of damage in buildings over an area in the event of severe earthquakes.

In this paper, a method of estimating the seismic risk of a group of buildings is discussed considering the variation of the seismic resistance capacity of actual reinforced concrete (RC) buildings and the variation of the seismic force. The results of investigation on the level of damage to all RC buildings located in Oroshi-machi area in Sendai in the event of 1978 Miyagi-ken-oki earthquake are presented and the interpretation of the damage by the present method is tried.

A PROCEDURE FOR THE PREDICTION OF EARTHQUAKE DAMAGE OVER AN AREA

The prediction of the percentage of damage to a group of RC buildings located in an urban area is considered. It is assumed that the indices for the seismic resistance capacity of buildings in an area and the earthquake force exerted on buildings are both modelled by the random variables having certain probability distributions.

The probability of failure, which can be read as the percentage of damaged buildings to all buildings in an area, is evaluated on the basis of classical risk analysis by assuming that the failure of building subjected to earthquake force is expressed by a simple inequality including the resistance index and the force index [1]. Each step in the evaluation procedure is discussed in the following.

REGIONAL SEISMIC RISK

Seismic risk of a region is evaluated by the investigation of historical informations on the large earthquakes which have affected the region considered. We consider Sendai city situated in the north-east (Tohoku) district of Japan as an example. Fig. 2 shows the distribution of annual maximum magnitude of earthquakes which have occurred within a specified region as shown in Fig. 1 during the period of 1885 to 1978. Two curves in Fig. 2 indicate

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the Gumbel, Type I and Type III, distribution models for the annual maximum magnitude. The Type III model is adopted for its good accuracy in the range of large magnitude in representing the seismic activity of the region.

$$F(M) = \mathrm{Prob}[X \leq M] = \exp\left[-\left(\frac{\omega - M}{\omega - u}\right)^{k}\right] \qquad 1)$$

where $\omega = 8.43$, $u = 5.89$, $k = 4.03$

Then we tentatively assume a hypothetical point source at the center of the region in Fig. 1. The magnitude of earthquakes which occur at this point source is assumed to follow the probability distribution by Eq. 1.

The average return period T_R is related to the probability distribution F(M) by the following equation.

$$T_R = 1 / (1 - F(M)) \qquad 2)$$

The value of M corresponding to a given T_R is obtained utilizing Eqs. 1 and 2. By assuming Kanai's attenuation law given by Eq. 3, the relation between the expected maximum ground acceleration A_{max} and the return period T_R is obtained as shown in Fig. 3. The epicentral distance Δ of 100 km and the focal depth z of 40 km are assumed.

$$A_{max}(gal) = \left(\frac{5}{\sqrt{T_G}}\right) \cdot 10^{0.61M - \left(1.66 + \frac{3.60}{x}\right)\log x + \left(0.167 - \frac{1.83}{x}\right)} \qquad 3)$$

where x = focal distance (km) = $\sqrt{\Delta^2 + z^2}$

T_G = dominant period of ground (sec)

EARTHQUAKE FORCE

The earthquake force is given in the form of the idealized response spectrum, the level of which is determined from the expected maximum ground acceleration. The response spectrum values are assumed to be the random variable having the lognormal distribution, the mean value of which is assumed to coincide with the model response spectrum. The Umemura's model spectrum is used here. The influence of soil condition is taken into account using the modification factor γ. The effect of damping ξ is considered by Eq. 6.

The mean value of the earthquake force index S is given as follows.

$$\mu_S = S_o \cdot \gamma \cdot \xi \cdot A_{max} / G \qquad 4)$$

where

$$S_o = \begin{cases} 3.6 & (T \leq 0.5 \text{ sec}) \\ 1.8/T & (T > 0.5 \text{ sec}) \end{cases} \qquad 5) \qquad \xi = \frac{1.5}{1 + 10h} \qquad 6)$$

γ = factor for soil condition, h = damping factor, G = 980 gal

The coefficient of variation for the earthquake force index is assumed to cover all inherent uncertainties and is taken to be 0.4.

RESISTANCE CAPACITY

The seismic resistance capacity of buildings is thought to be approximately expressed by the ultimate base shear coefficient C_Y introduced by Shiga, which is calculated from the total areas of columns and walls in one direction in the first story [2].

$$C_Y = (12A_c + 33A_w)/1300\sum A_f \qquad 7)$$

where A_c = total column area in the first story (cm^2)

A_w = total wall area in the first story (cm^2, include all RC walls)

$\sum A_f$ = total floor area (m^2), unit floor weight = 1300 kg/m^2

Shiga et al. investigated the variation of seismic resistance capacity of actual low-rise buildings in Tohoku district of Japan [2]. The number of buildings investigated is 245. They are 1 story to 5 story buildings and 3 story buildings are about one half.

The probability distribution of the seismic resistance C_Y is shown in Fig. 5. It is seen that the average value of the ultimate resistance of actual RC buildings is much higher than the nominal design value of 0.2, and that the variation in the ultimate resistance is so large that some portion of existing buildings may lack in redundant strength required to resist severe earthquakes. It has been recognized from the experience of recent earthquakes in Japan that the minimum strength of 0.2 specified by the code is sometimes not sufficient for low-rise buildings if they do not have enough ductility after yielding. The smooth curve in Fig. 5 is the lognormal distribution model for the probability density function of C_Y.

$$f(C_Y) = \frac{1}{\sqrt{2\pi}\,\zeta C_Y}\cdot \exp\left[-\frac{[\ln C_Y - \lambda]^2}{2\zeta^2}\right] \qquad 8)$$

where $\lambda = E[\ln C_Y] = 0.095$, $\zeta = \sqrt{E[(\ln C_Y - \lambda)^2]} = 0.423$

The index for the seismic resistance capacity R is assumed to be expressed by the random variable having the lognormal probability distribution, the parameters of which are determined based on the data of actual buildings.

EVALUATION OF DAMAGE PROBABILITY

The failure probability of buildings p_f is evaluated as follows.

$$P_f = \mathrm{Prob}[R \le \alpha S] = \mathrm{Prob}[Z \le \alpha], \quad Z = R/S \qquad 9)$$

The value of α can be related to the level of damage by assuming the energy conservation rule or displacement conservation rule on the elastic and inelastic earthquake response.

$$\alpha = \begin{cases} 1/\sqrt{2d-1} & \text{: energy conservation} \\ 1/d & \text{: displacement consevation} \end{cases} \qquad 10)$$

where d is the ductility factor corresponding to the level of damage considered. The energy conservation rule is adopted here.

Under the assumptions of lognormal distributions for both the resistance and force indices, the probability of failure is expressed as follows.

$$P_f = 1 - \Phi(\beta) \qquad 11)$$

where

$$\beta = \frac{\ln(\mu_R/\mu_S) - \ln\alpha - 0.5\ln\left(\frac{1+v_R^2}{1+v_S^2}\right)}{\sqrt{\ln(1+v_R^2)(1+v_S^2)}} \qquad 12)$$

Φ = standard normal distribution = N(0,1)
μ_R, μ_S = E[R], E[S] = averages of resistance and force
σ_R^2, σ_S^2 = $E[(R - \mu_R)^2]$, $E[(S - \mu_S)^2]$ = variances of resistance and force
$\upsilon_R, \upsilon_S = \sigma_R/\mu_R, \sigma_S/\mu_S$ = coefficients of variation of resistance and force

Therefore, p_f is expressed as the function of the ratio of mean values μ_R/μ_S and the coefficients of variation υ_R, υ_S. Figs. 6 and 7 show the effects of various parameters in Eqs. 11 and 12.

MODEL STUDIES

Consider two hypothetical models of RC building groups in Sendai region. The one represents low-rise RC buildings located in an alluvial area (Case A), and the other represents middle-height RC buildings located in a diluvial area (Case B). Properties of each building model are shown in Table 1. The value of T_G is assumed to be 0.3 sec. The soil factors are assumed to be 2.0 and 1.2 for Case A and Case B, respectively. The value of ductility factor d corresponding to the damage level is tentatively assumed as shown in Table 1.

Given the return period, the probability of failure, i.e., the percentage of expected damage, can be calculated for each case as shown in Table 2.

DAMAGE TO RC BUILDINGS IN OROSHI-MACHI AREA

The investigation was conducted on all RC buildings in Oroshi-machi area in Sendai where the structural damage to RC buildings was most severe in 1978 Miyagi-ken-oki earthquake [3]. Oroshi-machi area is a merchandise area of about 550000 m^2 newly developed in 1966 - 1973 (Figs. 9 and 10). The soil deposit of the site consists of an alluvial layer of about 3 m, a gravel layer of about 20 m and the Pliocene base rock. The number of all RC buildings is 193, most of which are 2 and 3 story. The percentage of observed damage in RC buildings is shown in Table 3.

The distribution of the ultimate resistance capacity of RC buildings in Oroshi-machi area was investigated as shown in Fig. 11. Fig. 12 shows the relation between the probability of damage and the earthquake force based on the data of resistance capacity in Oroshi-machi. The ground acceleration in Oroshi-machi is estimated as 0.3-0.4G, though no strong motion records have been obtained in this area. Assuming the ground acceleration of 0.35G and the amplification by building of 2.7, the probability of damage is calculated as 29 % for d =1 (small damage) and 8 % for d = 2 (medium damage). These values can be compared to the values in Table 3. It is also inferred from the figure that if the intensity of earthquake motion had been slightly higher, the damage might have been significantly heavy.

CONCLUSIONS

A method for the assessment of potential damage in RC building groups in the event of earthquakes is discussed considering the variations of both the resistance capacity and the earthquake force. Continuous investigations are needed to evaluate realistic distributions in seismic resistance as well as earthquake force.

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2) Shiga, T., "Earthquake Damage and the Amount of Walls in Reinforced Concrete Buildings", 6WCEE, New Delhi, Jan. 1977, pp. 7_49-52
3) Shiga, T., Shibata, A., et al., "Investigation of All RC Buildings in Oroshi-machi Area in 1978 Miyagi-ken-oki Earthquake", Tohoku Branch Symposium, Architectural Institute of Japan, Nov. 1978, pp. 105-116 (Japanese)

Table 1 Assumed Properties for Building Group Models

Model	Resistance Capacity μ_R	ν_R	Period (representative value)	Damping h	Soil Factor γ	Ductility Factor for Damage Level d: Level 1	Level 2
A	1.2	0.4	0 - 0.5 sec (0.25)	0.1	2.0	1.0	2.0
B	0.6	0.4	0.5 - 1.0 (0.75)	0.05	1.2	1.5	3.0

Table 2 Percentage of Damage for Building Group Models

Return Period T_R (year)	A_{max} (gal)	Case A Level 1	Case A Level 2	Case B Level 1	Case B Level 2
10	90	5.4 %	0.5 %	1.7 %	0.2 %
20	125	15	2.2	6.2	0.8
40	163	30	6.2	15	2.7
60	186	38	9.7	21	5.4
80	203	45	13	26	7.2
100	216	49	15	37	8.1

Table 3 Percentage of Observed Damage in RC Buildings in Oroshi-machi in 1978 Miyagi-ken-oki Earthquake (Revised)

Damage Level	Number of Buildings	Percentage of Damage	Cumulative Percentage
Collapse	3	1.6 %	1.6 %
Heavy Damage$^{1)}$	5	2.6	4.2
Medium Damage$^{2)}$	9	4.7	8.9
Small Damage$^{3)}$	32	16.6	25.5
No Damage	144	74.5	100.0

1) = needs extensive repairs to structural elements or needs demolition
2) = needs partial repairs to structural elements
3) = needs repairs to secondary elements

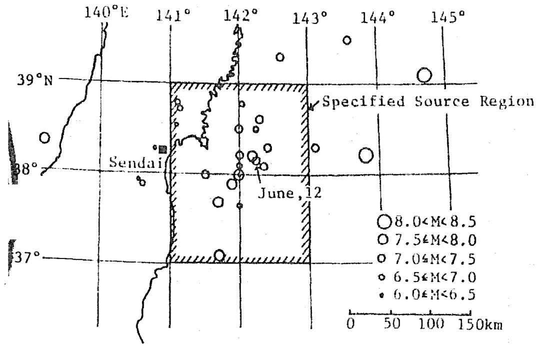

Fig. 1 Occurrence of Earthquakes Around Sendai Region

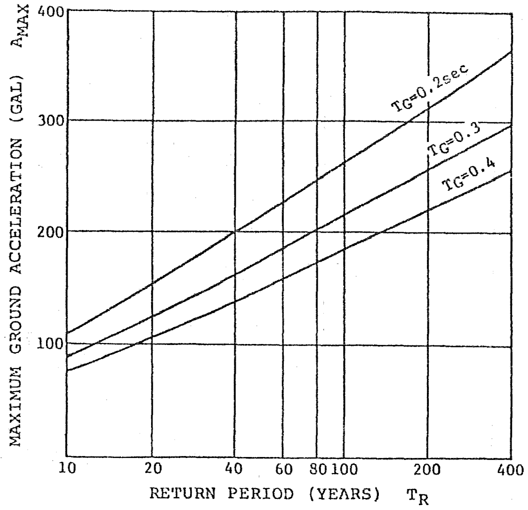

Fig. 3 Expected Maximum Ground Acceleration

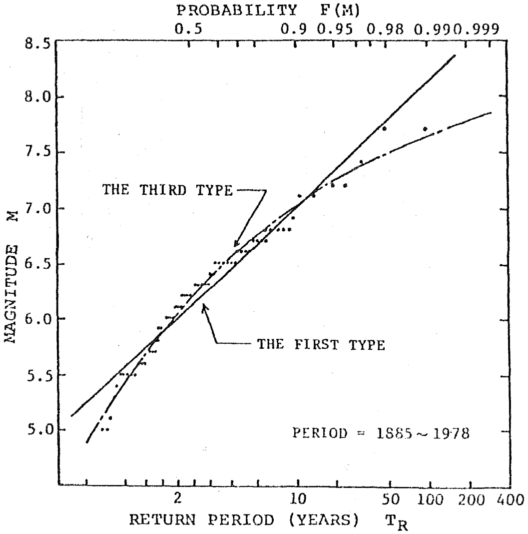

Fig. 2 Probability Distribution of Annual Maximum Earthquake

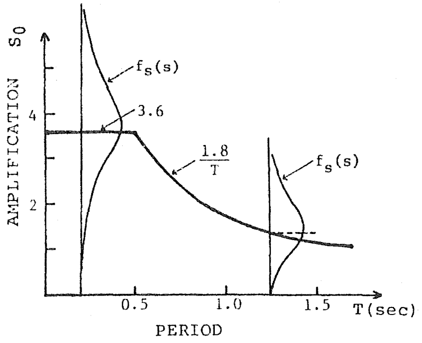

Fig. 4 Idealized Acceleration Response Spectrum

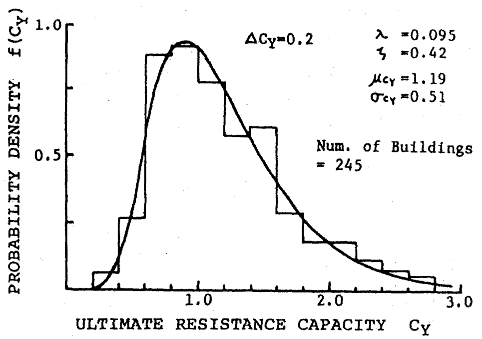

Fig. 5 Distribution of Ultimate Strength of RC Buildings in Tohoku District

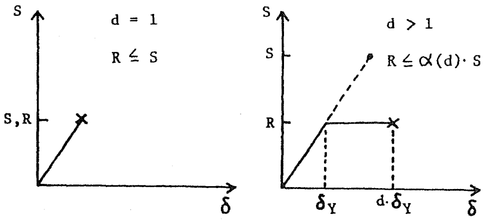

Fig. 6 Definition of Building Failure with Relation to Damage Level

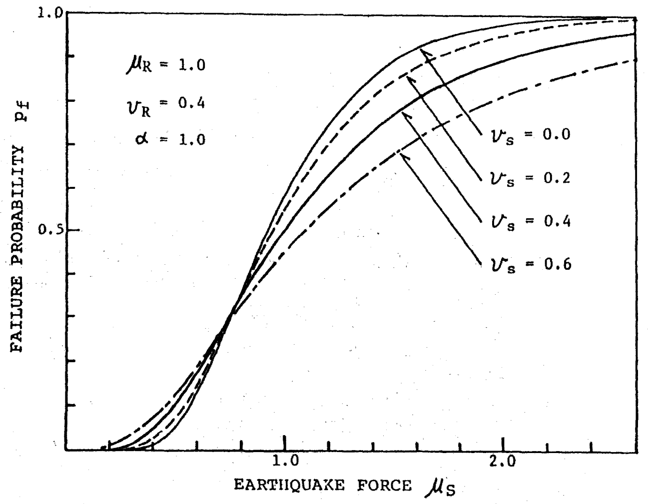

Fig. 7 Effect of Variation in Force on Failure Probability

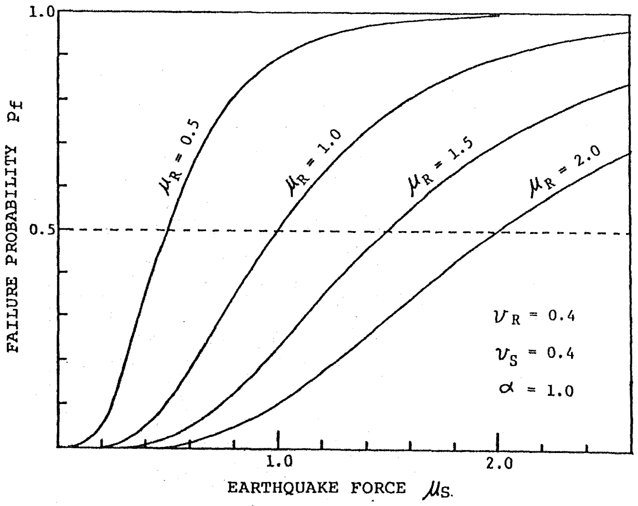

Fig. 8 Effect of Level of Registance on Failure Probability

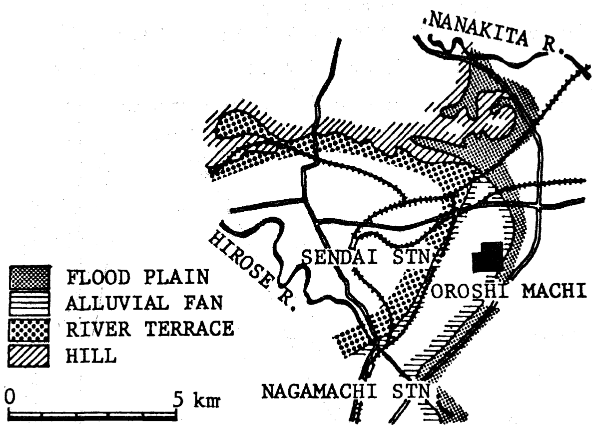

Fig. 9 Geological Map of Sendai Region and Location of Oroshi-machi

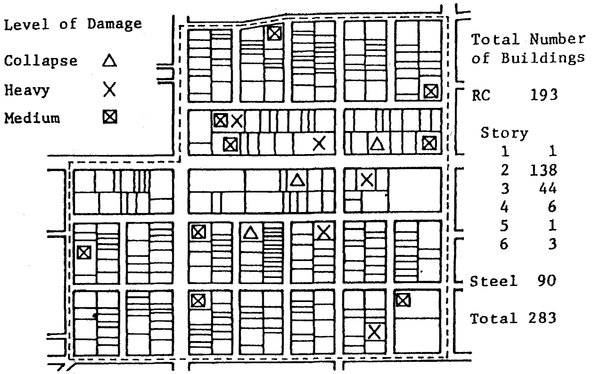

Fig. 10 Damaged RC Buildings in Oroshi-machi in 1978 Miyagi-ken-oki Earthquake

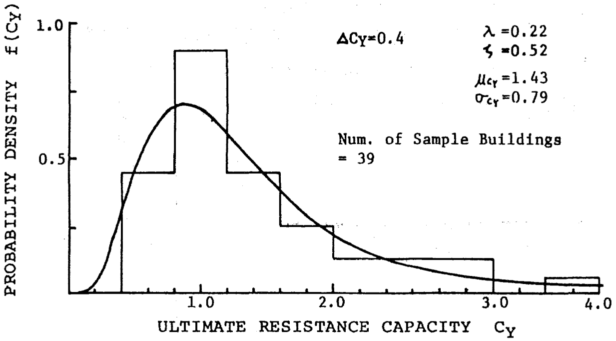

Fig. 11 Distribution of Ultimate Strength of RC Buildings in Oroshi-machi

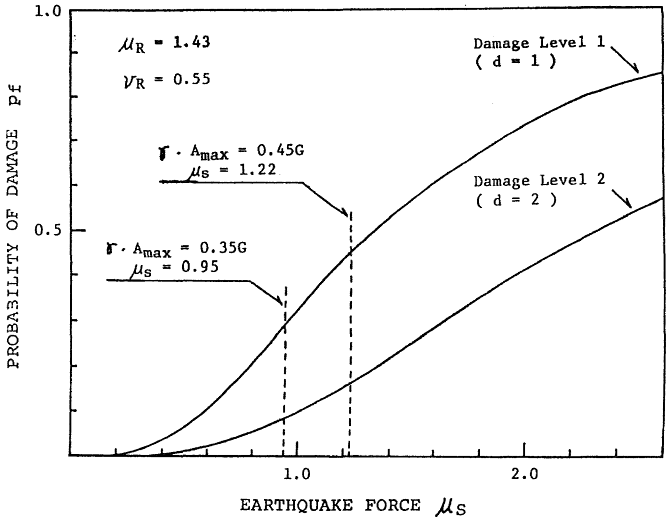

Fig. 12 Estimated Probability of Damage in Oroshi-machi