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SEISMIC VULNERABILITY ASSESSMENT OF REINFORCED CONCRETE BUILDINGS USING MICROTREMOR MEASUREMENTS

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SUMMARY

using microtremor measurements. The seismic vulnerability is evaluated by a stochastic-fuzzy integrated method. Microtremor measurements are used to identity the fundamental periods and damping ratios of buildings and the underlying soil. The interstory drift and eccentricity of buildings are calculated by a random vibration theory, taking into account the inelastic response of buildings and soil and variability of model parameters. Damage states are quantified in terms of a damage measure by using membership functions. Earthquake damage functions that relate the interstory drift and eccentricity to the damage measure are derived by using past seismic damage data. To show the applicability of the seismic vulnerability assessment, the future damage states of existing reinforced concrete buildings are predicted against assumed offshore and inland earthquakes at a specific are

INTRODUCTION

earthquake (M=7.2, 1995) caused unprecedented damage on Kobe. More than 5,500 people were killed and a number of building structures suffered severe damage or collapse. Urban function had been inactivated for a long time due to destruction of infrastructures such as transportation and lifeline systems. To prevent and mitigate such a seismic disaster, it is useful and helpful to assess the seismic vulnerability of building structures at a specific area in advance.

A variety of seismic vulnerability assessments have been proposed by, *ex*., [Bouhafs, 1986] and [Scawthorn *et al*., 1981]. In these studies, seismic damage is evaluated by using past damage data as well as empirical and theoretical models deterministically or probabilistically. It is relatively easy to calculate structural response, but not easy to evaluate structural damage quantitatively. The way of evaluating the ambiguous damage state has been presented by [Yao, 1985] using a fuzzy set theory. It is well known that the earthquake response and damage depend heavily on dynamic properties of buildings and the underlying soil. Microtremor measurements have been used to estimate the predominant period of soil by [Kanai and Tanaka, 1954]. Microtremor measurements have been also used to identify dynamic properties of different types of building structures. These properties can be used to construct the transfer functions of buildings and soil. Recently, microtremor measurements have been applied to evaluate the seismic vulnerability of wooden houses by [Uehan and Nakamura, 1996] and RC buildings by [Hamamoto *et al*., 1997]. The reason why microtremor measurements are useful is mainly due to the daily acquisition of measurement data, the easy installation of measurement device and the low cost compared to artificial excitations such as vibration or impulse generator tests. However, there are some problems to use microtremor measurements in the seismic vulnerability assessment. One of the problems is the translation from dynamic characteristics of structures and soil under microtremor to those under earthquake ground motion. Another problem is the reliability and accuracy of microtremor measurements in the noisy urban environments.

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problems is the translation from dynamic characteristics of structures and soil under microtremor to those under earthquake ground motion. Another problem is the reliability and accuracy of microtremor measurements in the noisy urban environments.

In this study, a simplified seismic vulnerability assessment of RC buildings is proposed by using microtremor measurements of buildings and soil. The vulnerability assessment is formulated by a stochastic-fuzzy integrated method. The stochastic responses are calculated by a stationary random vibration theory, taking account of structural and soil nonlinearities as well as statistical uncertainties. Seismic damage states are predicted by using earthquake damage functions that are derived for offshore and inland earthquakes by a fuzzy set theory. Application examples are presented to show the applicability of the proposed method.

2. OVERALL FRAMEWORK

The overall framework for evaluating the seismic vulnerability of RC buildings using microtremor measurements is shown in Fig.1. Dynamic properties of buildings and soil are characterized by their fundamental periods and damping ratios. These parameters are estimated by microtremor measurements and prior information such as soil boring data and structural documents. Soil proprieties under microtremor are translated to those under earthquake ground motion because of their strong strain dependent nature.

A source-path-site-structure system is considered in the seismic vulnerability assessment. Assuming the magnitude and fault distance of an offshore or inland earthquake, the earthquake intensity at bedrock is determined by an attenuation curve. Site response is calculated by multiplying the earthquake intensity by the site transfer function estimated by microtremor measurements, taking account of the frequency dependent nature of soil. Structural response is calculated by multiplying the site response by the structural transfer function estimated by microtremor measurements and translating to the inelastic response by an equivalent energy concept, if necessary.

Both vertical and horizontal stiffness distributions play important roles in the seismic vulnerability assessment. As shown in Fig.2, dynamic properties of translational and torsional vibrations are estimated by microtremor measurements. The interstory drift is calculated from translational response, whereas the eccentricity from torsional response. The future seismic damage states of building structures are predicted by using earthquake damage functions that relate the interstory drift and eccentricity to the damage measure for offshore and inland earthquakes, respectively.

3. PARAMETER ESTIMATION

An inference system is developed to estimate dynamic parameters in the transfer functions of buildings and soil by using microtremor measurements as well as prior information as shown in Fig.3. Microtremor measurement is a powerful tool to estimate dynamic parameters of buildings and soil in an inductive way. Measurement data are recorded by locating a measurement device at different places in buildings and on ground. Parameter estimation is carried out by a random decrement method in the time domain and a spectral analysis in the frequency domain. An estimation in the time domain is usually more accurate than in the frequency domain, although the frequency domain technique is more tractable than the time domain technique. Measurement data are processed using different filtering and smoothing. Consequently, estimated parameters have random uncertainties.

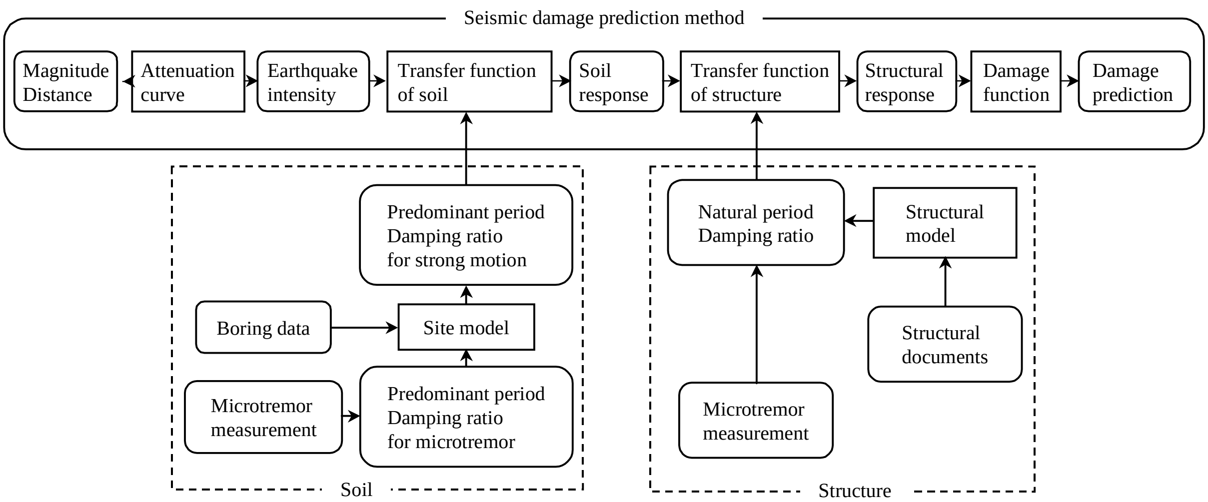


Fig.1 : Seismic vulnerability assessment using microtremor measurements.

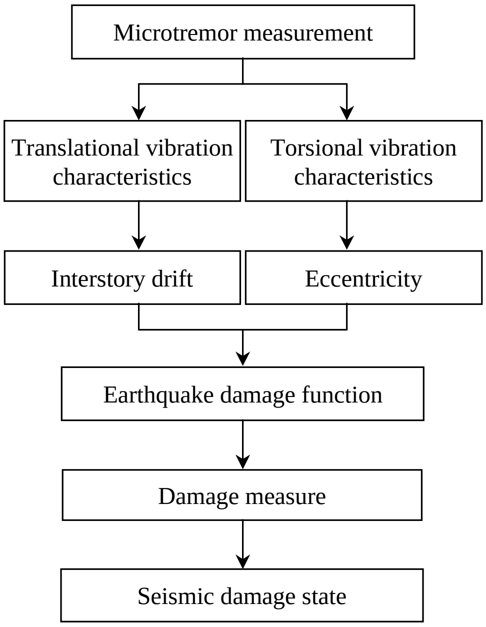


Fig.2 : Vertical and Horizontal damage evaluation.

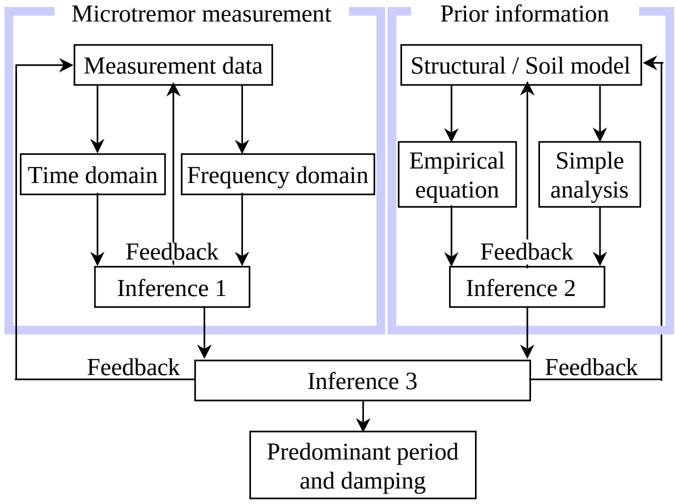


Fig.3 : Estimation of predominant periods and damping ratios of Buildings and Soil.

It is not an easy task to obtain the reliable and accurate results of microtremor measurements, because the meaningful information is easily disturbed by different sources of noise in urban areas. To overcome this problem, prior information such as structural documents and soil boring data are used to evaluate dynamic parameters of buildings and soil in a deductive way by existing empirical equations and simplified theoretical models, taking into account statistical variability. In Fig.3, Inference 1 and 2 are used to update and improve each result of microtremor measurements and prior information, respectively, whereas Inference 3 is used to integrate both results of microtremor measurements and prior information. The final outputs are used as dynamic parameters in the transfer functions of buildings and soil, respectively.

4. STOCHASTIC RESPONSES

The attenuation equation proposed by [Fukushima-Tanaka, 1991] is used to relate the earthquake magnitude and fault distance of an offshore or inland earthquake to the earthquake intensity at a site. The maximum acceleration on ground surface is given by

$$\log S_A = 0.51M - \log(X + 0.0006 \cdot 10^{0.51M}) - 0.0034X + 0.59\,, \qquad (1)$$

where S_A is the maximum acceleration, M is the earthquake magnitude and X is the fault distance. Figure 4

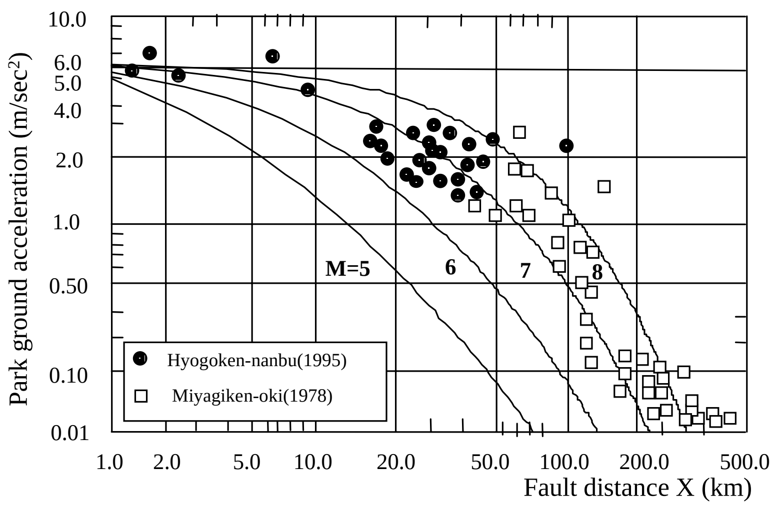


Fig.4 : Attenuation curves.

shows attenuation curves together with recorded data on Hyogoken-nanbu (1995) and Miyagiken-oki (1978) earthquakes. The variability in attenuation curve is disregarded in this study. The spectral intensity, G_0, at bed rock can be related to the maximum acceleration, S_A, by the Kanai-Tajimi power spectral density function [Tajimi, 1960] as

$$G_0 = \frac{4h_G (S_A / g_G)^2}{\pi\omega_G (1+4{h_G}^2)}, \tag{2}$$

where ω_G and h_G are the circular frequency and damping ratio of soil, respectively, and g_G is the peak factor. The mean and standard deviation of g_G are respectively given by [Davenport, 1964] as

$$m_G = \sqrt{2\ln \nu_0^+ t_0} + \frac{0.557}{\sqrt{2\ln \nu_0^+ t_0}}, \qquad \sigma_G = \frac{\pi}{6\sqrt{2\ln \nu_0^+ t_0}}, \tag{3}$$

where t_0 is the earthquake duration and ν_0^+ is the zero-upcrossing rate approximated by $f_G = \omega_G / 2\pi$.

Using dynamic parameters estimated by microtremor measurements, the transfer function of the underlying soil are given by

$$H_G(\omega) = \frac{2ih_G\omega_G\omega + {\omega_G}^2}{-\omega^2 + 2ih_G\omega_G\omega + {\omega_G}^2}, \tag{4}$$

where ω_G and h_G are translated from those under microtremor to those under earthquake ground motion by a computer program SHAKE [Schnabel *et al*., 1972].

A building structure is idealized as a one-degree-of-freedom system. The transfer function of the building is given by

$$H_S(\omega) = \frac{1}{-\omega^2 + 2ih_S\omega_S\omega + {\omega_S}^2}, \tag{5}$$

where ω_S and h_S are the circular frequency and damping ratio of building, respectively. Structural parameters estimated by microtremor measurements are directly used to construct the transfer function of the building.

If buildings behave elastically, the maximum displacement at the top of building, δ_e, can be calculated as

$$\delta_e = g_S \sqrt{G_0 \int_0^\infty \left| H_G(\omega) H_S(\omega) \right|^2 d\omega}, \tag{6}$$

where g_S is the peak factor. The mean and standard deviation of g_S are given by Eq. (3) where ν_0^+ is approximated by $f_S = \omega_S / 2\pi$. Buildings are damaged if structural response goes into the inelastic range, whereas they are not damaged if structural response remains within the elastic range. Assuming the interstory drift at a yield point as $\Delta_y = 0.0044$ [Bouhafs, 1986], the linear response may be translated to the nonlinear response by using an equivalent energy concept. The interstory displacement of the *i-th* story may be evaluated by

$$\delta_i = \left[\frac{i}{N}\right]^B \delta_p, \tag{7}$$

where B is the coefficient which represents the shape of displacement distribution [Scawthorn *et al*., 1981] and N is the number of stories.

The vertical stiffness distribution is expressed by the following parameter,

$$R_{si} = \frac{Nrs_i}{\sum rs_i}, \tag{8}$$

where rs_i is the inverse of interstory drift, $\Delta_i = \delta_i / H_i$, and H_i is the height of the *i-th* story. Δ_i is the function of N, B, H_i, ω_G, h_G, ω_S, h_S, g_G, g_S and Δ_y. Among them, N, B, H_i and Δ_y are deterministic variables and ω_G, h_G, ω_S, h_S, g_G and g_S are random variables in this study. The means and coefficients of variation of R_{si} are calculated to evaluate parameter uncertainties. The smallest value of R_{si} is taken as a damage parameter.

The horizontal stiffness distribution is expressed by the following parameter,

$$R_{ei} = \frac{e_{yi}}{r_{exi}}, \tag{9}$$

where e_{yi} is the eccentric distance of the *i-th* story and r_{exi} is the spring radius which is estimated by microtremor measurements of torsional vibration. The largest value of R_{ei} is taken as a damage parameter.

5. DAMAGE PARAMETERS

Damage states of low-to-middle-rise reinforced concrete buildings are shown in Fig.5. Damage states are classified into 5 stages: no damage, light damage, moderate damage, severe damage and collapse. The damage states are subjectively judged according to the most probable damage description.

A damage measure D ($0 \leqq D \leqq 1$) is introduced to quantify the damage state. To describe the ambiguity of the definition and boundary of each damage state, membership functions are appropriately established for each damage state as shown in Fig.6. The mean value of each damage state is: 0.05 for no damage, 0.2 for light damage, 0.4 for moderate damage, 0.7 for severe damage and 0.85 for collapse, respectively.

The relationship between damage measure, D, and damage parameters, R_s and R_e, is shown in Fig.7. The auxiliary parameters, $\overline{R}_s$ and $\overline{R}_e$, which are defined by

$$\overline{R}_e = 2R_e \, , \; \overline{R}_s = 1 - R_s \, , \tag{10}$$

are used for vertical and horizontal axes, respectively. The circle contours of damage measure, D, are observed in Fig.7. Therefore, an integrated parameter, R, can be defined by

$$R = \sqrt{\overline{R}_e^{\,2} + \overline{R}_s^{\,2}} \, , \tag{11}$$

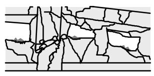
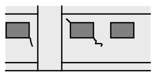
$\mu_i(D)$	Damage state	Description of damage	
$\mu_5(D)$	Collapse	Building partially or totally collapsed	
$\mu_4(D)$	Severe damage	Major structural damage; possibly total non-structural damage	
$\mu_3(D)$	Moderate damage	Widespread, extensive non-structural damage; readily repairable structural damage	
$\mu_2(D)$	Light damage	Minor, localized non-structural damage	
$\mu_1(D)$	No damage	No or insignificant structural damage	

Fig.5 : Damage states of RC buildings.

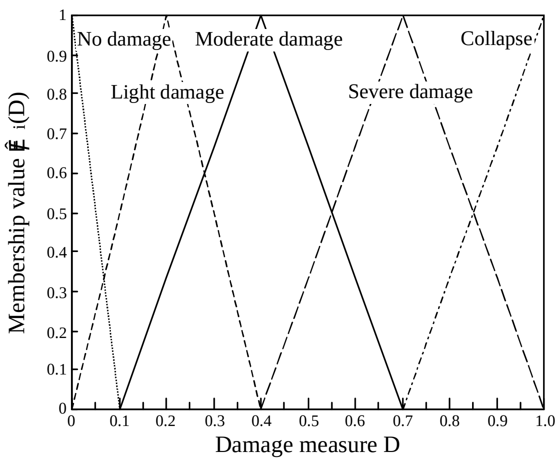


Fig.6 : Membership functions of damage state.

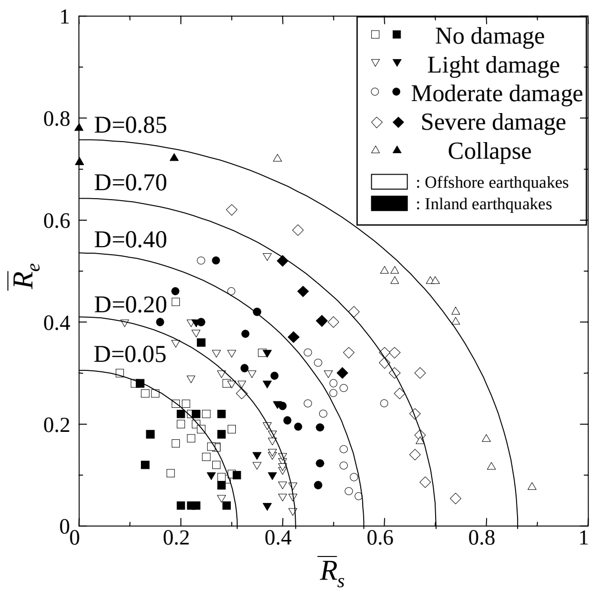


Fig.7 : Seismic damage contour.

6. SEISMIC DAMAGE FUNCTION

To construct earthquake damage functions that relate the damage parameter, R, to the damage measure, D, for offshore and inland earthquakes respectively, 106 existing damage data of low-to-middle-rise reinforced concrete buildings are used for offshore earthquakes, whereas 70 existing damage data are used for inland earthquakes. Most of the damage data for offshore earthquakes are those of Miyagiken-oki earthquake [Architectural Institute of Japan, 1978], whereas all of the damage data for inland earthquakes are those of Hyogoken-nanbu earthquake [Architectural Institute of Japan, 1995]. Figure 8 shows two earthquake damage functions for offshore and inland earthquakes. Each function is described by the mean and standard deviation. With the increase of the damage parameter, R, the damage measure, D, increases monotonically. The general shape of both damage functions is a slowly varying S-shaped curve. If the damage measure has the same value, the mean of R for inland earthquakes is always less than that for offshore earthquakes. Thus, the damage increases more rapidly with R for inland earthquakes than for offshore earthquakes. The variability of inland earthquakes is larger than that of offshore earthquakes.

7. APPLICATION EXAMPLES

To show the applicability of the method, the future seismic damage of low-to-middle-rise reinforced concrete buildings that are located at the western part of Tokyo is predicted for assumed offshore and inland earthquakes. Figure 9 shows building sites and the location of assumed seismic faults. The rupture of Sagami trough (M=7.9) is presumed for an offshore earthquake, whereas the rapture of Tachikawa fault (M=7.2) for an inland earthquake.

The seismic vulnerability assessment is performed for four school buildings. Buildings A and B are 4 story and Buildings C and D are 3 story RC buildings. The plan of each buildings is shown in Fig.11. Buildings C and D are L-shapes. However, each wing is rigidly connected for D, whereas it is separated by expansion joint for C. Buildings A and B are located on the alluvial deposits of Tama river, whereas Buildings C and D are located on the plateau of Kanto loam as shown in Fig.10. The predominant periods and damping ratios of buildings and the underlying soil are estimated by microtremor measurements. The predominant period and damping ratio of soil are translated to those corresponding to each earthquake ground intensity.

Table 1 shows the results of seismic vulnerability assessment of four buildings. The means and coefficients of variation (COV) of the damage parameter, R, is calculated. The corresponding damage measure is determined by earthquake damage functions given by Fig.8. Then, damage states are represented verbaly by selecting the damage state with larger membership value for the damage measure shown in Fig.6. Ground accelerations are mutually close for offshore and inland earthquakes at all sites. However, damage states of buildings are different because of the different nature of offshore and inland earthquakes. The damage is more severe for inland earthquake than offshore earthquake. The structural damage of Buildings B and C is relatively small, while Building D suffers the largest damage. In this example case, since the fundamental period of building is far from that of soil for all buildings, the effect of soil condition on structural damage is relatively small. The vertical

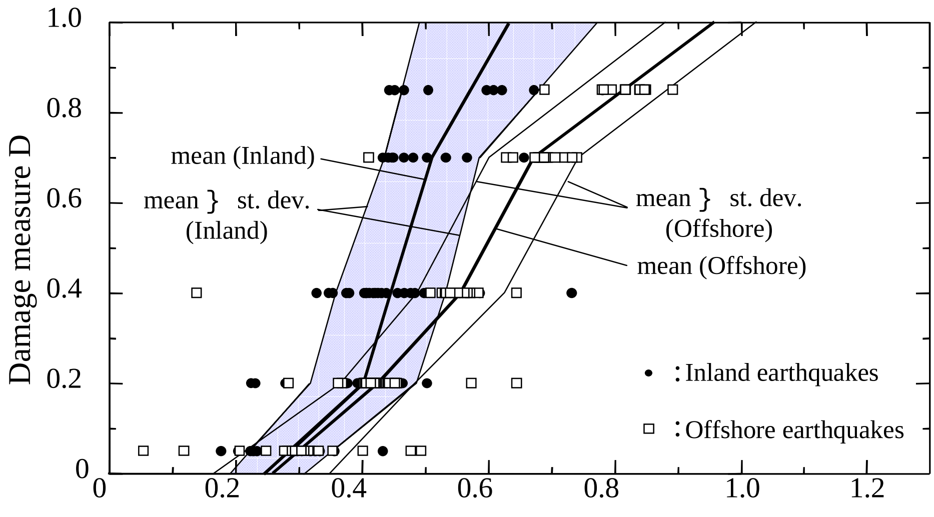


Fig.8 : Earthquake damage functions.

Table 1 : Seismic damage prediction for assumed earthquakes.

Earthquake	Building@A S_A (m/sec^2)	R_s Mean(COV)	R_e Mean(COV)	R Mean(COV)	D Mean(COV)	Damage
Offshore	4.11	0.57 (0.26)	0.05 (0.20)	0.44 (0.33)	0.22 (0.26)	Light
Inland	4.31				0.39 (0.54)	Moderate

Earthquake	Building@B S_A (m/sec^2)	R_s Mean(COV)	R_e Mean(COV)	R Mean(COV)	D Mean(COV)	Damage
Offshore	4.11	0.61 (0.28)	0.06 (0.17)	0.41 (0.33)	0.18 (0.23)	Light
Inland	4.25				0.26 (0.45)	Light

Earthquake	Building@C S_A (m/sec^2)	R_s Mean(COV)	R_e Mean(COV)	R Mean(COV)	D Mean(COV)	Damage
Offshore	4.06	0.60 (0.29)	0.05 (0.21)	0.41 (0.36)	0.18 (0.23)	Light
Inland	4.18				0.22 (045)	Light

Earthquake	Building@D S_A (m/sec^2)	R_s Mean(COV)	R_e Mean(COV)	R Mean(COV)	D Mean(COV)	Damage
Offshore	4.18	0.56 (0.33)	0.10 (0.19)	0.48 (0.38)	0.29 (0.32)	Light
Inland	4.05				0.54 (0.64)	Moderate

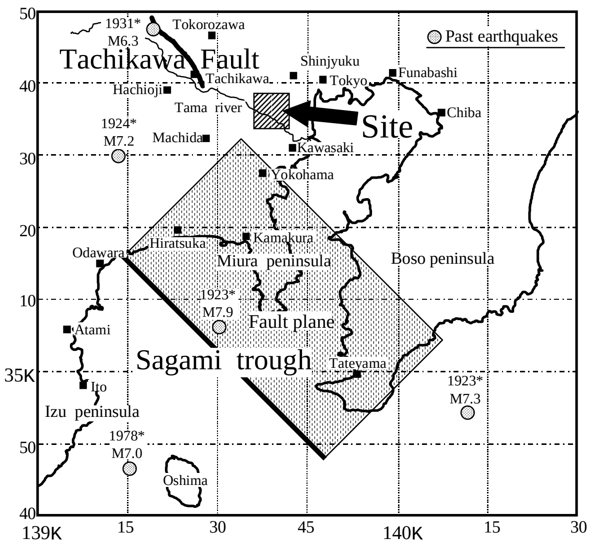


Fig.9 : Building sites and seismic sources.

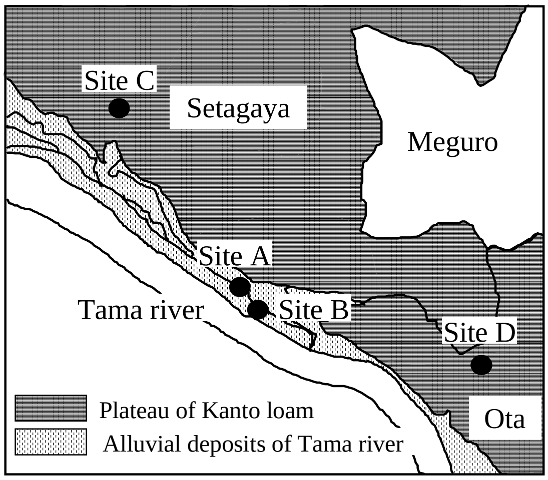


Fig.10 : Building sites and soil condition.

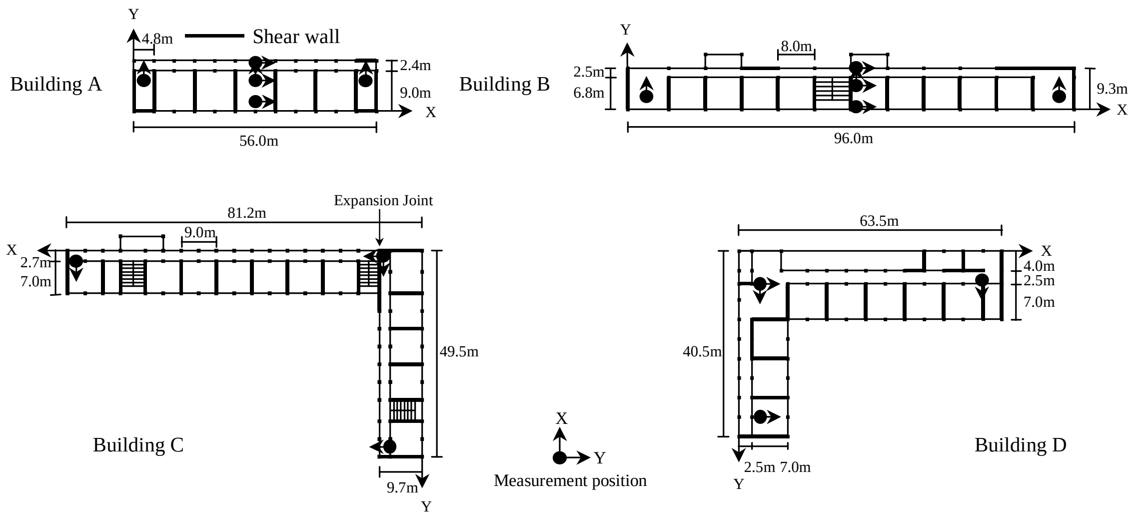


Fig.11 : Measurement points and directions for each building.

stiffness distribution is generally uniform in the case of school buildings. Consequently, the difference in damage state mainly comes from the torsional vibration associated with horizontal stiffness distribution.

8. CONCLUSIONS

A simplified method is presented to evaluate the seismic vulnerability of building structures using microtremor measurements. The seismic vulnerability is evaluated by a stochastic-fuzzy integrated method. Microtremor measurements are used to identity the fundamental periods and damping ratios of building structures and the underlying soil. Maximum interstory drift and eccentricity is predicted by a random vibration theory, taking into account the inelastic response of buildings and soil and variability of model parameters. Damage states are quantified in terms of a damage measure by using membership functions in a fuzzy set theory. Past seismic damage data are used to derive two earthquake damage functions that relate the interstory drift and eccentricity to the damage measure for offshore and inland earthquakes, respectively. To show the applicability of the method, the future damage states of existing reinforced concrete buildings are predicted against assumed offshore and inland earthquakes at a specific area. It is shown that the structural damage mainly depends on earthquake types, *i.e.,* offshore or inland, and the eccentricity of structures. Microtremor measurements are promising for the rapid seismic vulnerability assessment of individual buildings as well as building groups in urban areas because of the daily acquisition of data, easy installation of device and low cost.

9. REFERENCES

Architectural Institute of Japan (1979), *Report on damage investigation of the 1978 Miyagiken-oki earthquake*.

Architectural Institute of Japan (1997), *Report on the Hanshin-Awaji earthquake disaster -Structural damage to reinforced concrete building,* Maruzen.

Bouhafs, M. (1986), "Evaluation of the seismic performance of buildings", *Techniques for rapid assessment of seismic vulnerability, ASCE*, pp41-66.

Davenport, A. G. (1964), "Note on the random distribution of the largest value of a random function with application to gust loadings", *Proc. of Inst. of Civil Engineers, Vol.24*, pp187-196.

Fukushima, Y., Tanaka, T. (1990), "A new attenuation relation for peak horizontal acceration of strong earthquake ground motion in Japan", *Bull. Seism. Soc. Amer. 80*, pp757-783.

Hamamoto, T., Yu, J., Mori, H. (1997), "Seismic vulnerability assessment of building structures using microtremor measurements", *Proc. of the 7th ICOSSAR, Vol.3*, pp1611-1618.

Kanai, K., Tanaka, T. (1954), "Measurement of the microtremor I", *Bull. Earthq. Res. Inst., 27*, pp199-209.

Scawthorn, C., Iemura, H., Yamada, Y. (1981), "Seismic damage estimation for low-and mid-rise buildings in Japan", *Earthq. Eng.Struct. Dyn. Vol.9,* pp93-115.

Schnabel., P. B., Lysmer, J., Seed, H. B. (1972), *SHAKE-A computer program for earthquake response analysis of horizontally layered site*, Univ. of California, Berkeley.

Tajimi, H. (1960), "Statistical method of determining the maximum response of building structure during an earthquake", *Proc. of the 2nd WCEE, Vol.2*, pp781-798.

Uehan, F., Nakamura, Y. (1996), "Ground motion characteristics around Kobe city detected by microtremor measurement -the great Hanshin earthquake disaster-", *Proc. of the 11th WCEE*, Paper No.714.

Yao, J. T. P. (1985), *Safety and Reliability of Existing structures*, Pitman Pub.