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Seismic Microzonation Considering Long Period Components

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SYNOPSIS A methodology for characterizing the different levels of incident motion for microzonation is discussed. Relatively long period components, which dominate the nonlinear response of soft sites at higher level of excitation are suitably accounted for. Incident motions with the defined characteristics are generated by two step iteration scheme, and a seismic microzonation example based on the nonlinear response analysis of a soil profile database system is presented. Effectiveness of a new microzonation parameter, defined as Spectrum Intensity Amplification (SIA), to represent the extent of ground shaking hazard is examined and is found to represent well the damage pattern of wooden houses during a past earthquake.

INTRODUCTION

Seismic microzonation constitutes a long term seismic hazard analysis that represents the potential earthquake effects at a locality considering generation, transmission and local response in the earthquake process. The characterization and representation of the extent of incident excitation is central to seismic microzonation.

Local ground response can range from linear to highly nonlinear, depending on the ground condition and the level of incident excitation. Karkee *et al* (1993) have shown that long period components in the incident motion play increasingly dominant role as the nonlinearity in ground response increases. As a result, long period components need adequate consideration in the characterization of incident motion. This is particularly so in Japan, where most of the soil types encountered in urban areas begin to exhibit stiffness degradation at comparatively low strain levels.

A methodology that takes as input the historical seismicity data and the small motions from recent earthquakes recorded at one of the Sendai dense array site is presented for the characterization of the incident motion. Attempt is made to include fairly long period components.

Three levels of incident motion response spectra defined in the period range of 0.02 to 10.0 seconds, estimated to represent *frequent*, *medium* and *extreme* levels of incident excitation, are developed. Incident motions compatible to the corresponding response spectra are generated by two step iteration scheme (Karkee, 1993). Soil profile database system of Sendai area is utilized to carry out nonlinear response analysis under the action of the three levels of excitation. The results of the analysis are utilized to present a simple example of seismic microzonation.

LEVELS OF INCIDENT MOTION

The historical earthquake occurrence database system maintained by Japan Meteorological Agency (JMA) is utilized to define the *frequent*, *medium* and *extreme* levels of incident motion in terms of the seismic moment M_0 and the characteristic epicentral distance Δ_c. For this, the earthquake size-frequency distribution, considered as one of the fundamental relationship (Scholz, 1990), is utilized. One significant aspect of the size-frequency relation is that large and small earthquakes belong to different groups, and simple extrapolation of small earthquakes to predict large earthquakes leads to underestimation (Wesnousky *et al*, 1983). There is also the question of the variation in reliability of historical data. Our interest here is on larger earthquakes relevant to earthquake hazard evaluation. Larger earthquakes can be expected to have relatively better reliability because they tend to be remembered better than smaller ones. For this investigation, earthquakes of JMA magnitude M_J greater than 5 are assumed to belong to the larger earthquake group of size-frequency distribution.

The city of Sendai is the target study area. Its location is shown in Figure 1. The JMA database considered consists of the earthquakes occurring in the region between longitude 140°E to 144°E and latitude 36°N to 40°N during a 376 year period starting from 1616. Larger area to the east of Sendai is considered in recognition of the fact that major past earthquakes affecting Sendai, including the 1978 Miyagiken Oki earthquake, have originated in the plate boundary subduction zone in the Pacific ocean side.

Equation 1, developed by Fukushima and Tanaka (1991) based on the regression analysis of recent earthquakes in northern Japan, is utilized to estimate the seismic moment M_0 of historical earthquakes. To relate

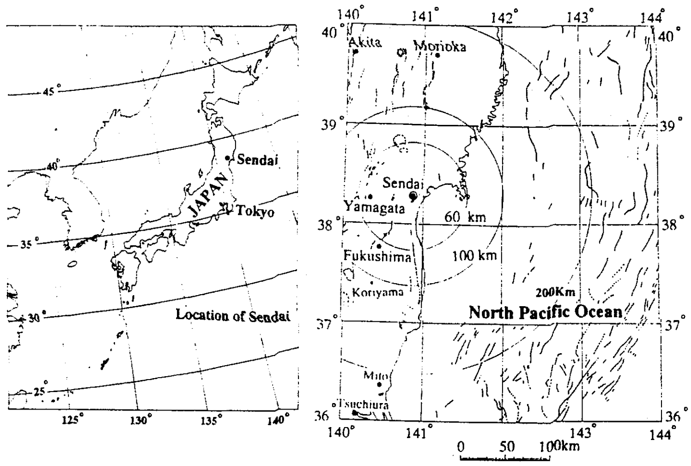

Fig. 1. Location of Sendai and the Region of Earthquake Occurrence Record

the occurrence rate with proximity from Sendai, three epicentral distance Δ ranges, 100 to 200 km, 60 to 100 km, and within 60 km are considered. The M_0-frequency distribution approximated by straight lines in Figure 2 are drawn to primarily represent the intermediate sizes. This is done in recognition of the fact that larger sizes are infrequent and tend to be under-represented in a data-set of limited duration, and the smaller ones tend to belong to different group as discussed above. The parameters a and B of the power law of Equation 2, which the number of earthquakes $N(M_0)$ of moment M_0 or greater is known to obey, were estimated from Figure 2 for each of the three Δ ranges.

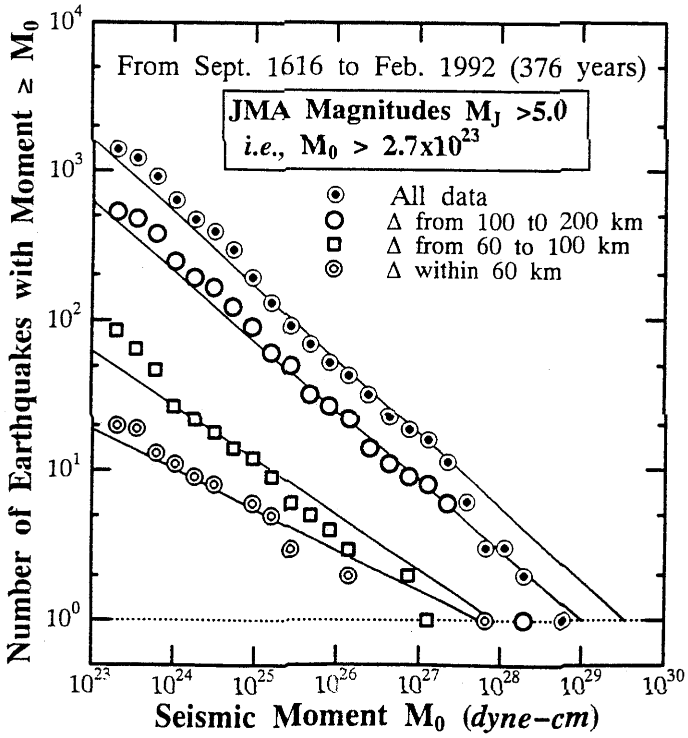

Fig. 2. Seismic Moment and Occurrence Frequency Relationship

$$log(M_0^{-1} + 10^{-17} M_0^{\frac{1}{3}}) = -1.1 M_J - 17.92 \quad (1)$$

$$N(M_0) = a M_0^{-B} \quad (2)$$

Different levels of earthquakes may be defined based on certain acceptable frequency of occurrence in a given locality. For this study, the earthquakes occurring once in 20 years are assumed to be *frequent*, and those that occur once in 50 years are assumed to be *medium*. The earthquake that is likely to occur once in the data-set duration is assumed to be *extreme*. The sizes in M_0 of the three levels of incident motion in each of the three Δ ranges are estimated from Equation 2.

To exercise some degree of conservatism to account for different sources of uncertainties, the earthquakes occurring in the Δ ranges of 100 to 200 km and 60 to 100 km are assumed to be characteristically represented by Δ_c = 100 km and Δ_c = 70 km respectively. The Δ range of within 60 km is assumed to be represented by Δ_c = 40 km, which is again conservative because large earthquakes are less likely to occur at closer proximity from Sendai. With these modifications, the incident motion sizes shown in Table 1 are considered for seismic microzonation of Sendai.

TABLE 1. Incident Motion Sizes Considered for Seismic Microzonation of Sendai

Earthquake level	$N(M_0)$	Magnitude M_J	M_0 (dyne-cm)	Δ_c (km)
Frequent	19	7.0	1.69×10^{26}	70
		7.5	3.66×10^{27}	100
Medium	7	7.0	1.69×10^{26}	40
		7.5	3.66×10^{27}	70
		8.0	1.46×10^{29}	100
Extreme	1	7.50	3.66×10^{27}	40
		8.0	1.46×10^{29}	70

INCIDENT MOTION RESPONSE SPECTRA

The response spectra are defined for one of the sites named TAMA in the Sendai dense array strong motion observation system (Figure 7). The latitude and longitude of the site are 38°15′12″N and 141°00′26″E respectively. Of the eleven sites in the array system, it is the only site belonging to ground type 1 (stiff site) according to the classification in the Japanese code for earthquake resistant design of buildings. The fundamental ground period T_G at TAMA is about 0.14 seconds.

The Ohsaki standard spectra defined in the period range of 0.02 to 2.00 seconds form part of the recommendations for nuclear power plant design in Japan. The standard spectra are defined for a peak horizontal velocity V_{max} of 10.0 Kine. To compute the actual response spectra, V_{max} for different earthquake sizes at the location considered is required. Fukushima and

Tanaka (1990) have presented a new attenuation relation of Equation 3 for the mean of peak horizontal acceleration from two horizontal components A (Gals) for Japan in terms of the focal distance Z (km) and surface wave magnitude M_s. They have used Equation 4 to estimate M_s from M_J. In addition, Sawada *et al* (1992) have published the regression relation for the maximum amplitude ratio A/V_{max} given in Equation 5. Equations 3, 4 and 5 are utilized for the estimation of V_{max} and hence the definition of Ohsaki standard spectra at TAMA site.

$$\log_{10} A = 0.41M_s - \log_{10}(Z + 0.032 \times 10^{0.41M_s}) - 0.0034 \times Z + 1.3 \quad (3)$$

$$M_s = 1.27 \times M_J - 1.82 \quad (4)$$

$$\frac{A}{V_{max}} = 41 \times 10^{-0.07M_J} \times \Delta_c^{-0.12} \times T_G^{-0.51} \quad (5)$$

Estimation of response spectral ordinates at relatively long period range is based on the prediction of large earthquakes from records of small earthquake motion. It is often referred to as the empirical Green's function method. The formulation is given by Aki and Irikura (1991) and expresses the ground motion of large earthquake yet to occur in terms of the small earthquake motion and the estimated fault parameters of the large earthquake. The fault plane of large earthquake is divided into $K \times K$ elements, when the seismic moment of large earthquakes is K^3 times that of the small one. Selected earthquake records at TAMA site are used as small earthquake motion. The fault parameters of large earthquakes are estimated based on the fault parameters of 1978 Miyagiken Oki earthquake and is summarized in Table 2. An example of the ground motions simulated by this method is shown in Figure 3.

The response spectra of a number of ground motions simulated by empirical Green's function method are utilized to estimate the incident motion response spectra at relatively long period range. The spectral ordinates of the Ohsaki spectra are retained in the short period range. Example of this comparison is shown in Figure 4.

TABLE 2. Fault Parameters of Large Earthquakes

	$M_J = 7.0$	$M_J = 7.5$	$M_J = 8.0$
M_0 (dyne-cm)	1.69×10^{26}	3.66×10^{27}	1.46×10^{29}
Fault strike	N190°E	N190°E	N190°E
Dip angle	20°	20°	20°
Length (km)	7.0	33.0	206.0
Down dip width (km)	80.0	80.0	80.0
V_R (km/sec)	3.2	3.2	3.2
V_S (km/sec)	3.7	3.7	3.7
Rise time (sec)	2	2	5
Focal depth (km)	40	40	40

V_R = Rupture Speed and V_S = Shear Wave Velocity

The three response spectra at 5% damping, representing the *frequent*, *medium* and *extreme* incident motions are shown in Figure 6 by thick smooth lines.

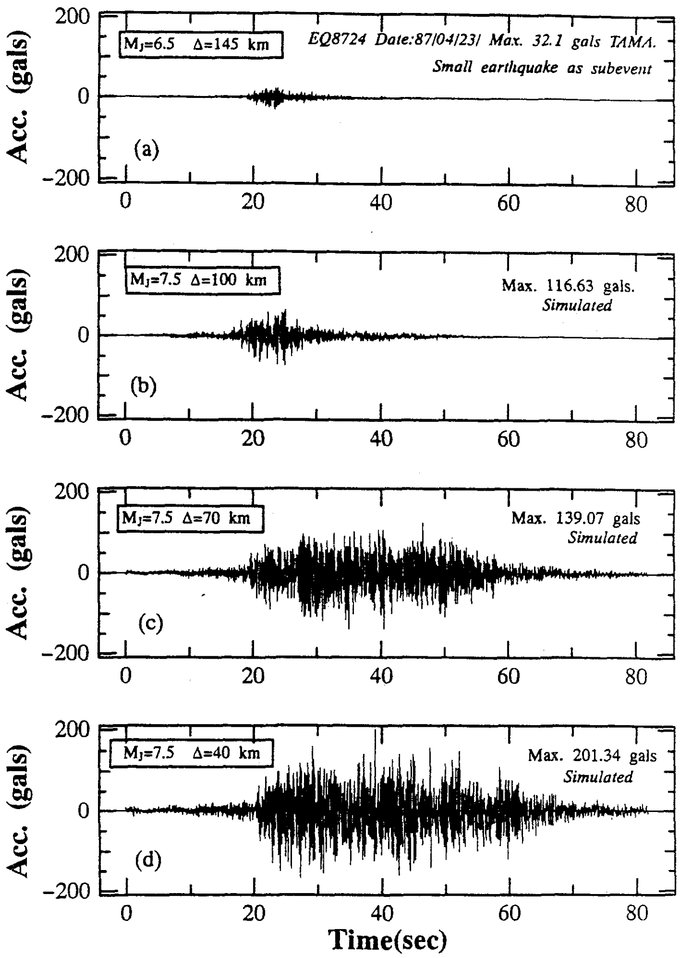

Fig. 3 Example of Ground Motions Simulated by Empirical Green' Function Method

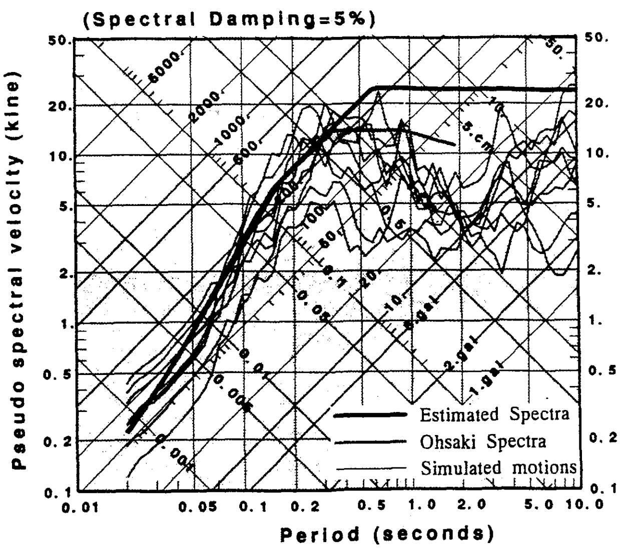

Fig. 4. Example of the Estimation of Incident Motion Response Spectra (*Frequent* Level)

GENERATION OF INCIDENT MOTIONS

The characteristics of the different levels of incident motion are suitably represented by response spectra. Incident motions compatible to the respective response spectra are generated by two step iteration procedure (Karkee, 1993), first in frequency domain and then in time domain. For iterations in the frequency domain, the close relation between the Fourier spectra amplitude and the response spectral velocity ordinate is utilized. The time domain iteration is based on the localized perturbation of the time history at the end of frequency domain iteration. It is found to be very effective in significantly improving the compatibility of the motion to the response spectra at long period range.

Initially the acceleration time history $a(t)$ is constructed to approximately match the target response spectra utilizing Equation 7, where $\mathbf{m}_j$ is replaced by spectral velocity ordinate $S_v(\omega_j)$ at the corresponding frequency ω_j. The phase angles ψ_j are made to vary uniformly between 0 and 2π by utilizing uniform random numbers. Following the nuclear power plant design method in Japan, the duration of motion T_D was estimated from $T_D = 10^{0.31M_J - 0.774}$. Durations corresponding to $M_J = 7.0, 7.5$ and 8.0 are assumed for frequent, medium and extreme levels respectively. The time function $E(t)$ of Equation 7 was utilized to define the overall character of incident motion. The value of C in Equation 7 was set to make $E(t) = 0.1$ at the end of duration T_D. Values of t_1, t_2 and C are shown in Table 3.

$$a(t) = E(t) \times \sum_{j=1}^{N} \mathbf{m}_j cos(\omega_j - \psi_j) \qquad (6)$$

$$E(t) = \begin{cases} (\frac{t}{t_1})^2, & \text{for } t \leq t_1 \\ 1, & \text{for } t_1 < t \leq t_2 \\ e^{-C(t-t_2)}, & \text{for } t_2 < t \leq T_D \end{cases} \qquad (7)$$

The time histories representing *frequent*, *medium* and *extreme* levels of incident motion are shown in Figure 5. The extent of matching to the corresponding response spectra can be seen to be very good in Figure 6.

TABLE 3. Constants of the Time Function

Level	T_D	t_1	t_2	C
Frequent	30.0	5.0	16.0	0.164
Medium	40.0	5.0	20.0	0.115
Extreme	52.0	4.0	24.0	0.082

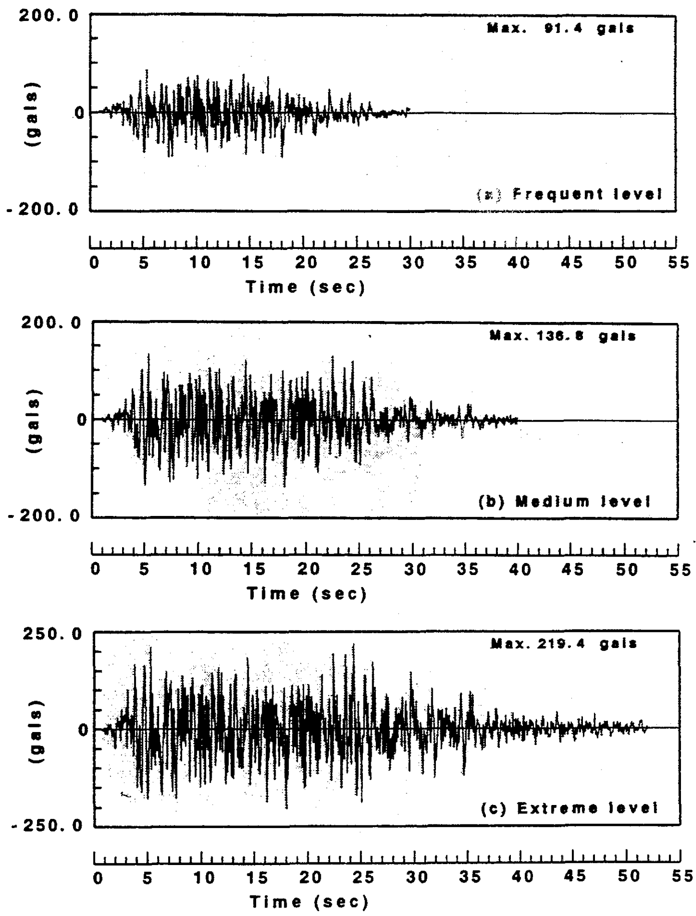

Fig. 5. Response Spectra Compatible Incident Motions at the End of Time Domain Iterations

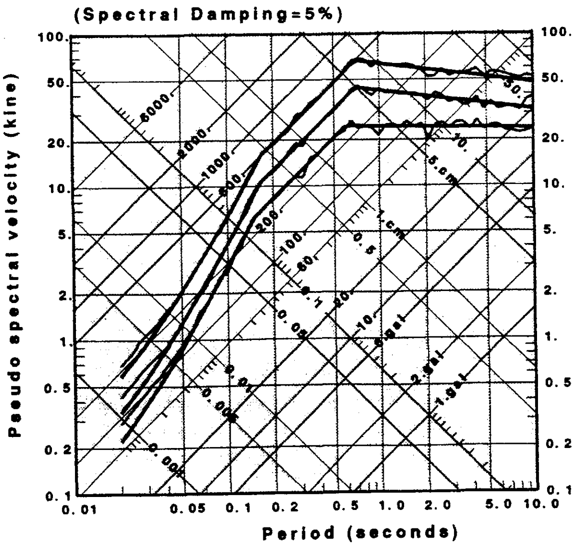

Fig. 6. Incident Motion Response Spectra and the Extent of Matching of the Respective Compatible Motions

SOIL PROFILE DATABASE

The soil profile database system of Sendai area bounded by latitude 38°10′N to 38°20′N and longitude 140°46′E to 141°05′E was originally developed by Sugimura (1980). Boreholes deep enough to reach the underlying soft rock layer are selected from the database. Of the more than 900 boreholes in the database, only 336 satisfied this condition. The area itself is divided into 620 blocks with a grid system of 30″ in latitude as well as in longitude. When the 336 boreholes are positioned in plan, only 132 blocks have at least one borehole. In the microzonation example presented below, each of the 132 blocks is represented by the nonlinear response of one or more boreholes within it.

NONLINEAR RESPONSE ANALYSIS

The soil types encountered in Sendai area can be broadly classified into clay, sand and gravel. The nonlinear behavior of these soil types is suitably modeled in the response analysis. The strain dependence of the shear modulus and the equivalent damping factor is based on Masing's type hysteretic model in combination with the nonlinear model of Ohsaki *et al* (1978), developed to represent average behavior of clay and sand found in Japan. The parameters of the model adjusted to adequately represent the behavior of clay, sand and gravel is explained in detail by Karkee (1993).

Assuming horizontally layered soil profile, the ground is modeled as a series of lumped masses connected by shear springs and dashpots. The nonlinear time domain response analysis is carried out by step-by-step numerical integration procedure using Wilson's θ-method developed by Ohsaki (1982). Viscous damping of 2% is assumed to represent damping in soil at initial condition. The *medium* level of incident motion is input at an exposed surface of base layer by considering a transmitting boundary represented by fictitious dashpot. The soft rock layer underlying Sendai area is considered as the base layer.

SEISMIC MICROZONATION EXAMPLE

The results of the nonlinear response analysis are utilized to present a seismic microzonation example of Sendai area. In their previous study on the measure of the extent of nonlinear ground response to various incident ground motions, Karkee *et al* (1992) had defined Spectrum Intensity Amplification (SIA) as a suitable parameter to represent local shaking hazard at a site to structures within a given period band. Attempt is made to utilize this new parameter in the microzonation example. For a given spectral damping, SIA is defined as shown in Equation 8. It is equivalent to the ratio of energy in the surface response motion to that in the incident motion in a period band between T_1 and T_2. $S_v(T)$ is the velocity response spectrum ordinate at a period T.

$$\mathrm{SIA} = \frac{\left|\int_{T_1}^{T_2} S_v(T)dT\right|_{\text{response}}}{\left|\int_{T_1}^{T_2} S_v(T)dT\right|_{\text{incident}}} \tag{8}$$

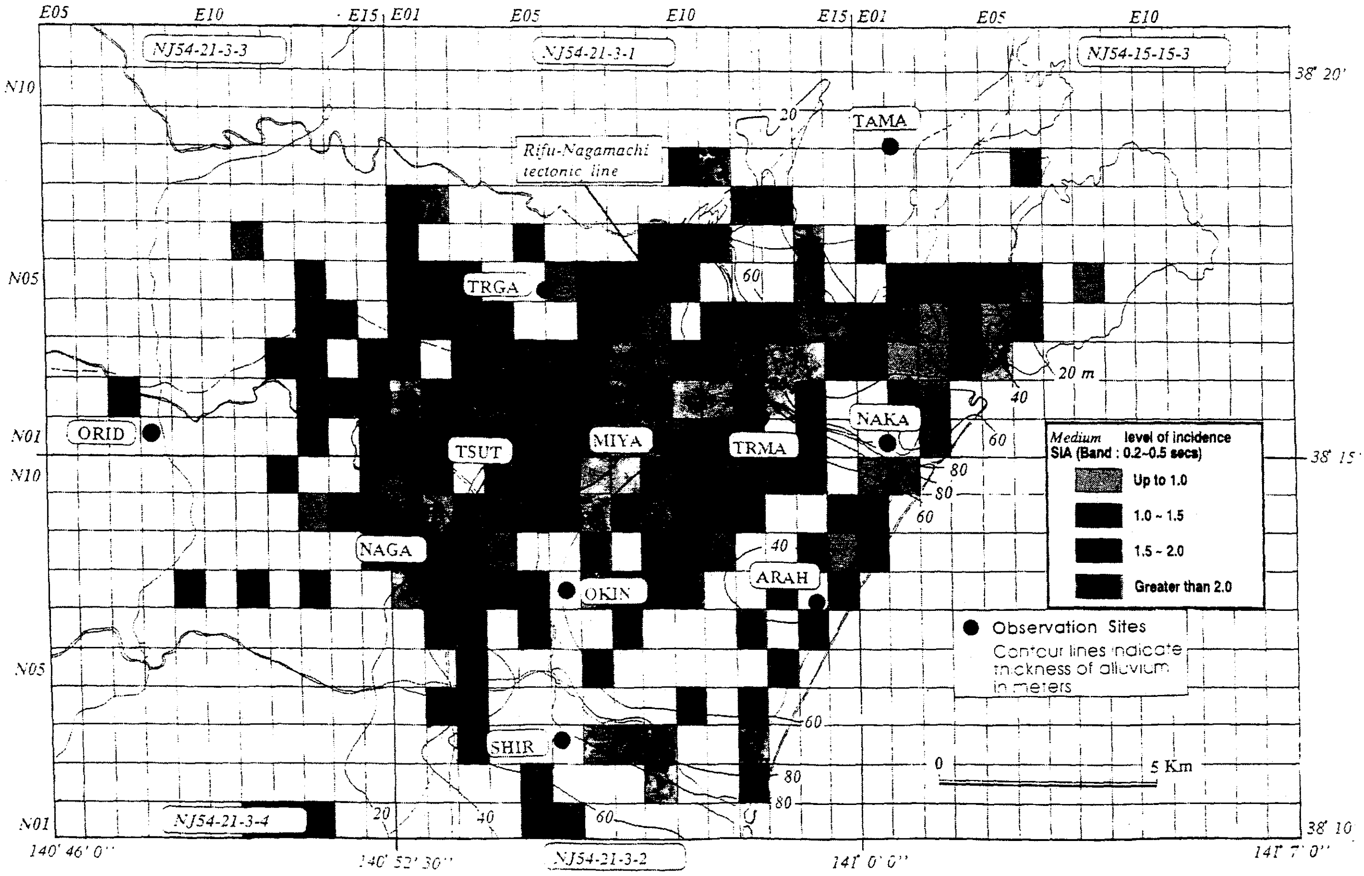

Fig. 7. Seismic Microzonation Example of Sendai Area Using SIA in the Period Band 0.2 to 0.5 Seconds

SIA is computed for three period bands, 0.2 to 0.5, 1.0 to 1.5, and 2.5 to 3.5 seconds, for all the sites analyzed for the *medium* level of incident excitation. The values are plotted by color coding in the grid system mentioned above. Average value is used when a grid is represented by more that one borehole. One of the plot for a period band of 0.2 to 0.5 seconds is shown in Figure 7. Similar plot is also prepared for maximum surface acceleration.

The circular dots in Figure 7 indicate the dense array observation sites and the contour lines show the thickness of alluvium. The Rifu-Nagamachi tectonic line, the fault line not known to be active in recent times, can also be noted. The tectonic line more or less delineates the relatively stiff sites to the north-west from the softer sites south-east towards the bay area (Sugimura, 1980).

At relatively short period band of 0.2 to 0.5 seconds, stiff sites to the north-west of tectonic line exhibit practically uniform SIA. In contrast, the distribution of the maximum acceleration shows large variation. Concentration of blocks with highest values of SIA is observed along a strip parallel to the tectonic line immediately to the south-east, which is not found to be evident in the plot of the maximum acceleration. The area around array station NAKA in Figure 7, which consists of very soft ground, is found to exhibit low values of SIA as well as the maximum acceleration. However, the same area indicates highest range of SIA value at period band of 1.0 to 1.5 seconds, rationally indicating the shaking hazard to relatively long period structures. At period band of 2.5 to 3.5 seconds, area to the north-west of tectonic line show SIA of one or less, while that to the south-east it is mostly greater than one.

SIA AND DAMAGE TO WOODEN BUILDINGS

The natural period of traditional two storied wooden family dwellings in Japan is said to range from 0.2 to 0.5 seconds, which is the period band of SIA in Figure 7. Sugimura (1980) has presented a microzonation of Sendai by damage to wooden buildings during the 1978 Miyagiken Oki earthquake. It is interesting to note that the higher values of SIA in Figure 7 correspond well to the area where concentrated damage to wooden buildings was observed.

CONCLUDING REMARK

A methodology for the characterization of incident motion for seismic microzonation considering the long period components and the different levels of excitation is demonstrated. Diversity of information used in the method indicate that a sincere effort at microzonation is a interdisciplinary endeavor. Seismic microzonation using SIA as a parameter has a promising application potential. When the period band is suitably selected to represent the range of natural period, higher value of SIA is seen to correspond well with the concentration of damage to wooden buildings in a past earthquake.

REFERENCES

Aki, K. and Irikura, K. (1992), "Characterization and Mapping of Earthquake Shaking for Seismic Microzonation", Proc *IV*: International Conference on Seismic Zonation, Stanford, 1:61-110.

Fukushima, Y. and Tanaka, T. (1991), "Scaling Relation for Earthquake Source Spectrum and JMA Magnitude", Journal of Struct. Constr. Engng., Transactions of Architectural Institute of Japan (AIJ), (425):19-25. (In Japanese).

Fukushima, Y. and Tanaka, T. (1990), "A New Attenuation Relation for Peak Horizontal Acceleration of Strong Earthquake Ground Motions in Japan", Bull. Seism. Soc. Am., 80(4):757-783.

Karkee, M. B., Sugimura, Y., Tobita J. and Sato, K. (1993), "Potential Effects of Long Period Components in Incident Motion on the Nonlinear Ground Response", Journal of Struct. Constr. Engng., Transactions of AIJ, (449):69-82.

Karkee, M. B. (1993), "Seismic Microzonation of Urban Areas Considering the Level of Excitation and the Local Soil Nonlinearity", Doctoral Dissertation, Dept. of Architecture, Faculty of Engineering, Tohoku University, Japan.

Karkee, M. B., Sugimura, Y. and Tobita, J. (1992), "Scaling a Suite of Ground Motions for Compatible Levels of Nonlinear Ground Response", Journal of Srtuct. Constr. Engng., Transactions of AIJ, (440):29-42.

Ohsaki, Y. (1982), "Dynamic Nonlinear Model and One Dimensional Nonlinear Response of Soil Deposits", Technical Research Report 82-02, Dept. of Architecture, University of Tokyo.

Ohsaki, Y., Hara, A. and Kiyota, Y. (1978), "Stress-Strain Model of Soil for Seismic Analysis", Proc *V*: Japan Earthquake Engng. Symposium, 697-704.

Sawada, T., Hirao, K. and Yamamoto, H. (1992), "Relation Between Maximum Amplitude Ratio ($a/v, ad/v^2$) and Spectral Parameters of Earthquake Ground Motion", Proc *X*: World Conference on Eartquake Engineering, Madrid, 2:967-972.

Scholz, C. H. (1990), "The Mechanics of Earthquake Faulting", Cambridge University Press, Cambridge.

Sugimura, Y. (1980), "An Attempt of Microzonation in and around Sendai", Proc *VII*: World Conference on Earthquake Engineering, Istanbul, 1:155-162.

Wesnousky, S., Scholz, C. and Shimazaki, K. (1983), "Earthquake Frequency Distribution and the Mechanics of Faulting", J. Geophys. Res., (88):9331-40.