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Estimation of the spatial distribution of ground motion parameters for two recent earthquakes in Japan

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Abstract

A recent development in strong motion instrumentation in Japan provides an opportunity to collect valuable data sets, especially after moderate and large magnitude events. Gathering and modeling these data is a necessity for better understanding of regional ground motion characteristics. Estimations of the spatial distribution of earthquake ground motion plays an important role in early-stage damage assessments for both rescue operations by disaster management agencies as well as damage studies of urban structures. Subsurface geology layers and local soil conditions lead to soil amplification that contributes to the estimated ground motion parameters of the surface. We present a case study of the applicability of the nationally proposed GIS-based soil amplification ratios [J. Soil Dyn. Earthqu. Eng. 19 (2000) 41–53] to the October 6, 2000 Tottori-ken Seibu (western Tottori Prefecture) and the March 24, 2001 Geiyo earthquakes in Japan. First, ground motion values were converted to those at a hypothetical ground base-rock level (outcrop) using an amplification ratio for each 1×1 km area, based on geomorphological and subsurface geology information. Then a Kriging method, assuming an attenuation relationship at the base-rock as a trend component, is applied. Finally, the spatial distribution of ground motion at ground surface is obtained by applying GIS-based amplification factors for the entire region. The correlation between the observed and estimated ground motion values is reasonable for both earthquakes. Thus, the proposed method is applicable in near real-time early-damage assessments and seismic hazard studies in Japan.

Keywords: The 2000 Tottori-ken Seibu earthquake; The 2001 Geiyo earthquake; Strong ground motion parameters; Attenuation relationship; Site amplification ratio; Digital national land information; Geomorphologic land classification; Kriging technique

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1. Introduction

Several recent damaging earthquakes in urban or suburban areas emphasize the importance of early damage assessment in earthquake disaster mitigation (Kanamori et al., 1997; Yamazaki et al., 1998; Wald et

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al., 1999a). Magnitude and depth information alone following a large magnitude earthquake cannot represent the complex damage pattern. More detailed information, including data obtained from a nationwide or a dense strong ground motion network, is required for decision-making by emergency management agencies and to reduce casualties (Heaton, 1985; Espinosa-Aranda et al., 1995; Nakamura, 1996; Wald et al., 1999b; Yamazaki, 2001; Wu et al., 2001). During a catastrophic earthquake, timely mapping of the spatial distribution of ground motion parameters such as peak ground acceleration (PGA), peak ground velocity (PGV), spectrum intensity (SI), and the instrumental Japan Meteorological Agency (JMA) seismic intensity (I_{JMA}) in near real-time is crucial to an effective rescue and emergency-response operation. In fact, GIS-based estimation of ground motion values can be used for construction of fragility curves for particular structures where strong motion stations are sparse.

Several site-response estimation methods have been proposed empirically in terms of nuclear explosions (Borcherdt, 1970), seismic coda wave propagation (Aki and Chouet, 1975; Tsujiura, 1978), and ambient noise (Aki, 1957; Okada et al., 1987; Nakamura, 1989; Bard, 1998). The ground motion distribution can be estimated by attenuation relationships that express the source, path, site effects, and, occasionally, the influence of other variables (Joyner and Boore, 1981; Campbell, 1985; Abrahamson and Shedlock, 1997; Fukushima and Tanaka, 1990; Molas and Yamazaki, 1995; Shabestari and Yamazaki, 1998; Chang et al., 2001). However, ground motion distributions are highly affected by local site and subsurface geology conditions. The strong influence of site effects has been recognized and studied for almost two centuries (Aki, 1988; Field, 2000).

Many researchers have identified the correlations between strong ground motion parameters and geology/site classifications. Tinsley and Fumal (1985) mapped quaternary sedimentary deposits for the Los Angeles basin that may affect strong earthquake ground motions. Borcherdt (1994) and Anderson et al. (1996) quantified the influence of subsurface geologic deposits on site response for southern California. Wills et al. (2000) proposed a site-condition map for regional seismic-hazard mapping evaluation for California by grouping geologic units with expected similar shear-wave velocity characteristics.

In Japan, several research studies have been conducted on the development of seismic hazard mapping systems. For the Kanto region, Matsuoka and Midorikawa (1995) developed a GIS-based amplification ratio for PGV using the correlation between the average S-wave velocity up to 30 m (AVG 30) from 459 sites in the region and Digital National Land Information (DNLI) data. Using earthquake damage assessment studies in Aichi Prefecture and Nagoya City (Nobi region), Fukuwa et al. (1998) prepared amplification ratios for PGA and PGV based on elevation, geomorphology, and the subsurface geology in the DNLI. Recently, Yamazaki et al. (2000) proposed a method to estimate amplification ratios for strong ground motion parameters that is applicable for all of Japan. They compared the relationship between the geomorphological and geologic conditions of the JMA free-field strong motion stations nationwide and the amplification ratios determined from the attenuation equations based on the JMA strong motion records. The GIS-based DNLI classification was employed to predict unique amplification ratios for PGA, PGV, and I_{JMA} for a square kilometer mesh that covers all of Japan.

In this study, we apply the proposed soil amplification ratios (Yamazaki et al., 2000) to two recent moderate-magnitude earthquakes in Japan as a practical example in damage assessment for a large area. The results are compared with the results estimated by attenuation models for both events.

2. Strong motion data

Two recent earthquakes (see Table 1) in Japan, which provided us with reliable data sets, was

Table 1
Description of the fault parameters of two recent earthquakes in Japan (Yagi and Kikuchi, 2000 and 2001)

	The October 6, 2000 Tottori-ken Seibu earthquake	The March 24, 2001 Geiyo earthquake
Magnitude	M_{JMA}=7.3 (M_{W}=6.6)	M_{JMA}=6.7 (M_{W}=6.8)
Focal depth	11 km	50 km
Fault type	Left lateral	Normal
Fault surface area	20×10 km	10×20 km
Strike, dip, slip	150° 87°, 1°	179°, 55°, −82°

recorded by the strong motion networks of the National Research Institute for Earth Science and Disaster Prevention (NIED) named K-NET (Kinoshita 1998) and KiK-net. The October 6, 2000 Tottori earthquake, with JMA magnitude of 7.3 (M_W=6.6), depth of 11 km, and left-lateral faulting, occurred in western Japan. The main rupture started 2.5 s after the nucleation and ruptured over a length of 20 km and width of 10 km (Yagi and Kikuchi, 2000). The Geiyo earthquake struck March 24, 2001 (Mjma=6.7, M_W=6.8) when a normal faulting system caused a unilateral rupture that propagated from north to south. The major slip occurred at a depth of 50 km on a fault 25 km long and 10 km wide. Joint inversion results using strong ground motion and teleseismic data (Yagi and Kikuchi, 2001) identified two large asperities and a maximum dislocation of 1.9 m. These two events caused slight to moderate damage to structures and lifeline facilities as well as soil liquefaction at the several areas near the coastlines of Hiroshima and western Tottori Prefectures. In order to investigate the ground motion characteristics and to capture surface variation in ground motion indices, we calculated PGA, PGV, I_{JMA}, and SI from the available strong motion records. Records with a PGA less than 1 cm/s^2 in one horizontal component were excluded. The shortest distance from each recording station to the fault plane was calculated using the model of Yagi and Kikuchi (2000, 2001). The final data sets consist of 329 and 454 three-component acceleration records, respectively. Fig. 1 demonstrates the variation of PGA with respect to PGV values. The maximum PGA and PGV values in the horizontal component were in excess of 900 cm/s^2 and 100 cm/s, respectively (Fig. 1a) and were recorded at station TTRH02 of Hino KiK-net. During the 2001 Geiyo earthquake, the maximum PGA and PGV was registered as 800 cm/s^2 and 30 cm/s, respectively at the Yuki K-NET (HRS009) station (Fig. 1b).

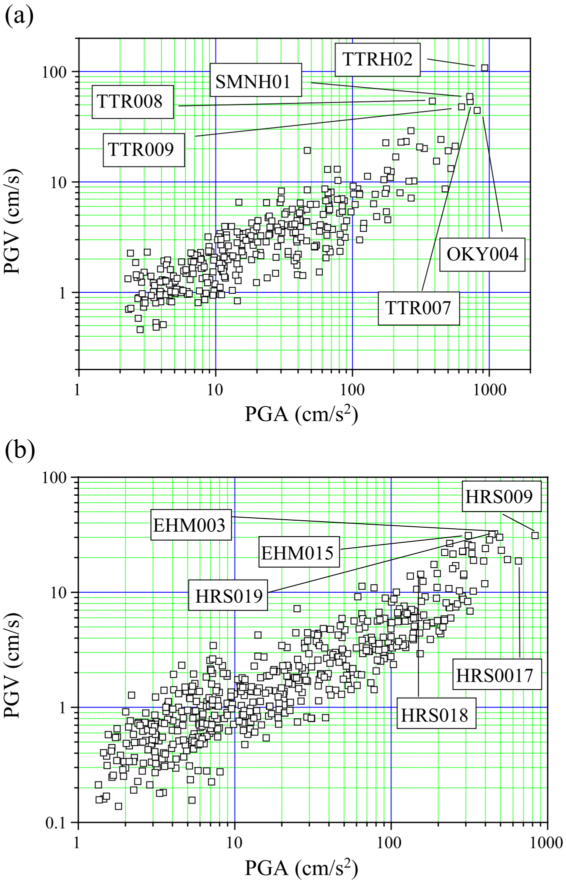

Fig. 1. Relationship between the observed PGA and PGV for K-NET and KiK-net stations. (a) The 2000 Tottori earthquake and (b) the 2001 Geiyo earthquake. Station codes of K-NET and KiK-net networks are plotted in boxes for some near-field recording sites.

2.1. Instrumental JMA seismic intensity

In Japan, JMA intensity has been used as a measure of strong shaking, in addition to PGA and PGV, for many years. It was originally determined by the human judgment of JMA officers; but, in the early 1990s, JMA began moving to an instrumental seismic intensity and away from human judgment. In 1996, the JMA intensity scale was revised and a large number of seismometers measuring the JMA intensity were deployed throughout Japan (JMA, 1996). The JMA instrumental seismic intensity, which is obtained from three-component acceleration records, is currently broadcast through public TV and radio soon after an earthquake occurs. Disaster management agencies in Japan use the JMA intensities as the most important index for structural damage estimates due to earthquakes (Yamazaki, 1998). The details of JMA seismic intensity algorithms are given in Shabestari and Yamazaki (2001).

2.2. Spectrum intensity

Spectrum intensity (SI) is one of the ground motion indices that is used to estimate structural damage due to earthquakes. In Japan, the SI value is used as an indicator to shut off natural gas supplies after a damaging earthquake. Based on the seismic records and damage to gas pipes located in the vicinity of instruments from the 1995 Kobe earthquake, an SI value of 60 cm/s was set as the level of shaking to trigger mandatory shut-off of a city gas supply. Following this criterion, Tokyo Gas developed SI sensors (Katayama et al., 1998) that calculate the SI value within the sensor using horizontal acceleration records. Recently, the deployment of new SI-sensors (Shimizu et al., 2001) began in the Tokyo metropolitan area, and the super-dense seismic monitoring system (SUPREME), with 3700 new SI sensors, will be completed by 2007. The spectrum intensity is calculated as the area under the relative-velocity response spectrum with a damping ratio of 0.2 between the periods of 0.1 and 2.5 s, divided by the period interval. In this study, we used the vectoral composition of the two horizontal components for PGA, PGV, and SI.

3. Estimation of spatial distribution of strong motion parameters

3.1. Site amplification ratio

The amplification ratios for a 1×1 km mesh were calculated following the method proposed by Yamazaki et al. (2000) that correlates the average station factors (Shabestari and Yamazaki, 1998) and the 11 DNLI soil classification groups, which are based on geomorphological and subsurface geology conditions. First, the appropriate DNLI classification was assigned to each recording station and then the strong motion at the ground surface was converted to a base-rock level (outcrop) by applying amplification ratios for each group.

3.2. Attenuation relationships at the base level

There were sufficient numbers of the strong motion records from the two earthquakes to allow construction of attenuation relationship for each event. This eliminated the inter-event component of variability in the attenuation relations. The attenuation model, which includes near-source saturation effects, is given by

$$Y = b_0 + b_1 r + b_2 \log_{10}(r + d) + \varepsilon \tag{1}$$

in which Y is $\log_{10}$PGA, $\log_{10}$PGV, $\log_{10}$SI, or the I_{JMA}, r is the shortest distance to the fault rupture, the b_i's are the regression coefficients to be determined, d is the near-source saturation effect (in kilometers), and ε represents the error term. The terms $b_1 r$ and $b_2\log_{10}(r+d)$ represent anelastic attenuation and geometric spreading, respectively. The coefficient b_2 equals -1.89 (Tong and Yamazaki, 1996) for intensity and -1.0 for PGA, PGV, and SI. The near-source saturation term, d, was applied only to the geometric spreading term. This is because near-source anelastic attenuation is negligible compared with geometric spreading. Since the near-source data from the 2000 Tottori-ken Seibu earthquake used in this study were from a single earthquake, the saturation effect term, d, was assumed to be constant. An iterative nonlinear least square analysis was performed to estimate d. The error term ε was defined as the difference between the predicted ground motion parameters, (Eq. (1)), for a trial value of d and the corresponding recorded ground motion values. However, it should be noted that d was zero for the 2001 Geiyo earthquake since there was no evidence of near-source saturation effects (the shortest distance to the fault extension was more than 40 km).

The results of regression analyses for the strong motion parameters associated with the 2000 Tottori-

Table 2
Results of regression analyses for ground motion parameters at the base outcrop level for the 2000 Tottori and the 2001 Geiyo earthquakes

	The October 6, 2000 Tottori-ken Seibu earthquake					The March 24, 2001 Geiyo earthquake				
	b_0	b_1	b_2	d (km)	ε	b_0	b_1	b_2	b (km)	ε
PGA	4.467	−0.00477	−1.0	48.9	0.251	4.578	−0.00528	−1.0	0.0	0.258
PGV	2.580	−0.00048	−1.0	2.2	0.233	2.969	−0.00286	−1.0	0.0	0.254
SI	2.568	−0.00110	−1.0	1.7	0.255	3.131	−0.00396	−1.0	0.0	0.262
I_{JMA}	7.527	−0.00416	−1.89	5.0	0.496	8.695	−0.00956	−1.89	0.0	0.526

ken Seibu and the 2001 Geiyo earthquakes are given in Table 2. The mean PGA, PGV, SI, and I_{JMA} predicted by the attenuation relationships and the converted ground motion values at the outcrop level are plotted with respect to the shortest distance from the site to the fault plane in Figs. 2 and 3.

3.3. Stochastic kriging method with a trend component

The effects of surface layers were minimized by converting the observed values to the hypothetic ground base level. Kriging, a stochastic interpolation method, was used to estimate the spatial distributions of strong motion parameters at the base level. First an exponential autocorrelation function was assigned. Simple Kriging algorithm was selected that provided a minimum error-variance estimate of unsampled values from neighboring data low-pass filter allowed smoothing of details and extreme values from the original data set (Deutsch and Journel, 1998). In this study, we applied the simple Kriging technique assuming a prior trend component, since the underlying random function model is the sum of trend and residual components (Journel and Rossi, 1989):

$$Z(u) = m(u) + R(u) \tag{2}$$

where $Z(u)$ is the random variable model at location u, $m(u)$ is the trend component, which is modeled as a smoothly varying deterministic function of the coordinates vector u, and $R(u)$ is the residual component modeled as a stationary random function with a zero mean and covariance. The trend component (deterministic function) is assigned for the attenuation relation obtained at the base level. The residual component (random function) is defined

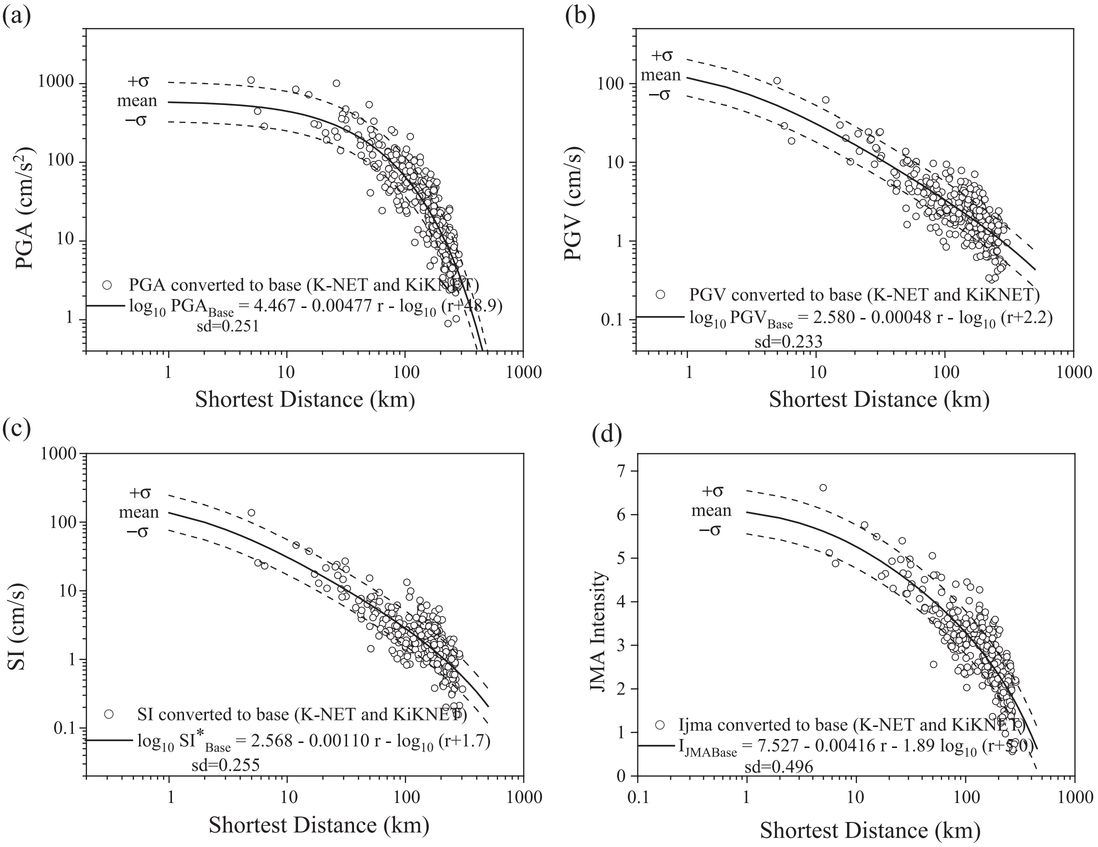

Fig. 2. Mean predicted PGA, PGV, SI, and I_{JMA} using the attenuation relationship (±1 standard deviation) at the base-rock (outcrop) level for the 2000 Tottori earthquake.

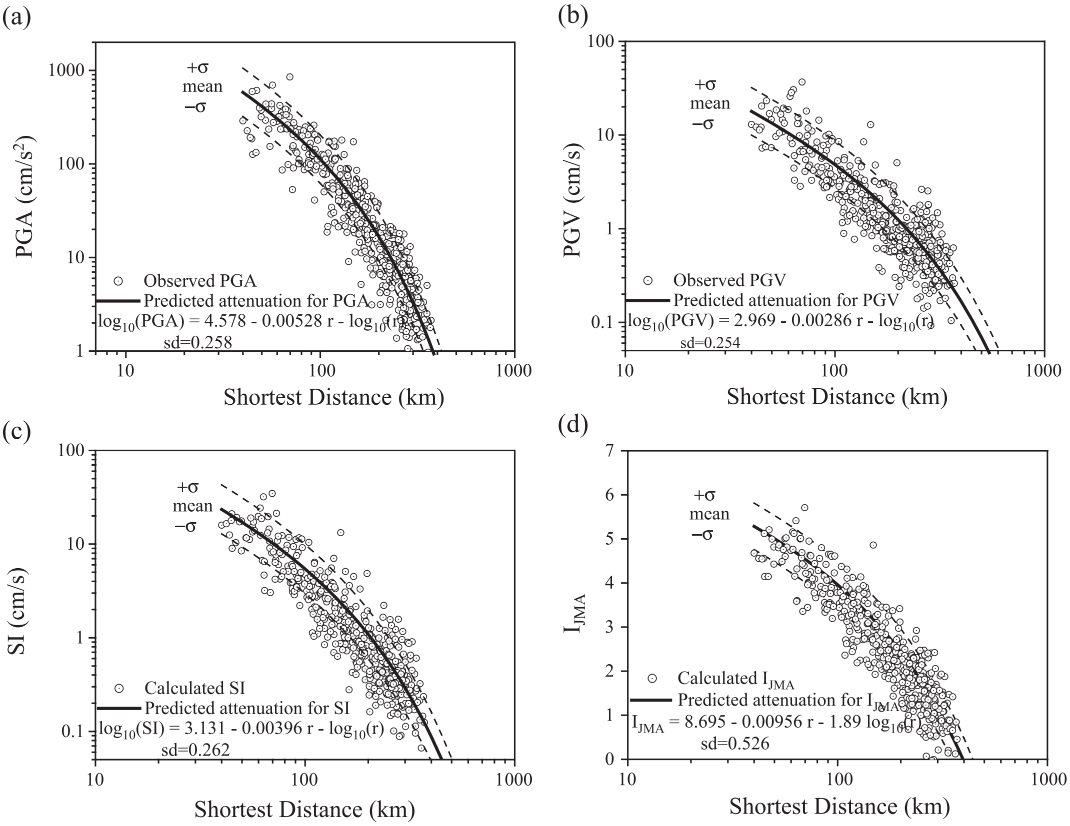

Fig. 3. Mean predicted PGA, PGV, SI, and I_{JMA} by the attenuation relationship (±1 standard deviation) at the base-rock (outcrop) level for the 2001 Geiyo earthquake.

as the difference between ground motions converted to the base level and the corresponding mean trend component values (Yamazaki et al., 1999):

$$R(u) = X_{\mathrm{b}i} - X_{\mathrm{m}i} \qquad (i = 1, \ldots, n) \qquad (3)$$

in which X is $\log_{10}$PGA, $\log_{10}$PGV, $\log_{10}$SI, or I_{JMA}, and the suffixes b and m represent the ground motion value at the base and the mean attenuation value, respectively, for n observations. Finally, the spatial distributions of the ground motion parameters at the ground surface are obtained by multiplying the corresponding GIS-based amplification ratio for each pixel.

4. Results and discussions

The spatial distributions of PGA, PGV, SI, and I_{JMA} for the 2000 Tottori-ken Seibu and the 2001 Geiyo earthquakes, with 79,996 and 120,376 grid points, respectively, were estimated for the selected regions. Those GIS-based grid points, corresponding to the 1×1 km pixels of the DNLI, were obtained using the Kriging method described in the previous section. The mapping results of the I_{JMA} are presented in Figs. 4 and 5. The estimated ground motion distribution maps look quite natural and match the observed values at the seismic stations. Individually constructing the attenuation relationships and introducing them into the deterministic function (the trend component) of the Kriging method resulted in realistic distributions of the estimated ground motion. The same method was applied to the previous study in Hyogoken Nanbu (Kobe) earthquake and resulted in a fair correlation between the estimated PGV distribution and the actual damage distribution of highway bridges (Yamazaki et al., 1999).

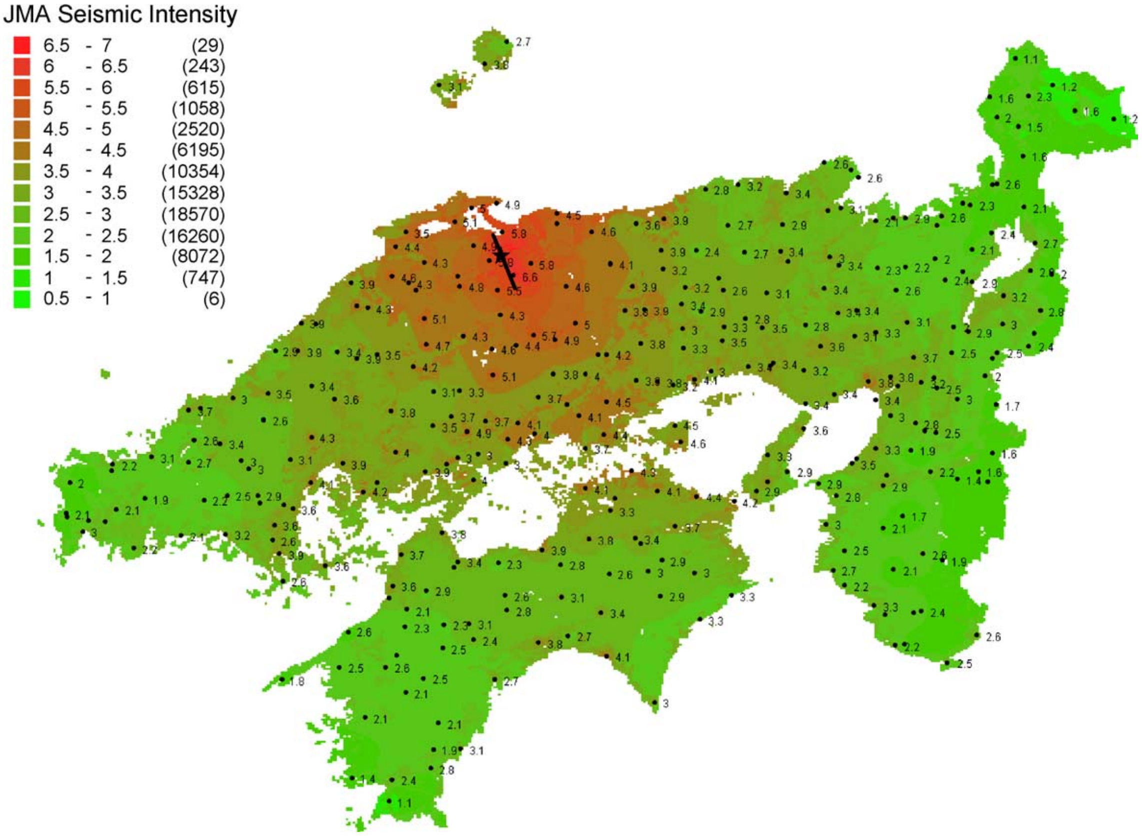

Fig. 4. GIS-based spatial distribution of the I_{JMA}, the epicenter (star), and the surface projection (thick line) of the fault plane for the 2000 Tottori earthquake. The result is shown for 1×1 km pixels of the DNLI. Plotted values are observed ones. To view this figure in colour, please see the online version of the paper.

4.1. Distribution of the observed I_{JMA} and empirically estimated values

As noted earlier, the instrumental JMA seismic intensity (I_{JMA}) scale is the most popular earthquake ground motion parameter among Japanese disaster-management agencies. To examine the accuracy of the I_{JMA} values estimated by the method herein, we compared them with observed I_{JMA} values at the K-NET stations. The empirically estimated I_{JMA} values were obtained using the attenuation relation of Shabestari and Yamazaki (1999). They developed attenuation relations for the ground motion based on source, path, depth, and station factor using accelerograph records of the K-NET network. Note that a zero mean value for the all K-NET stations is assumed for the station factor. Using the resulting attenuation coefficients, the mean predicted I_{JMA} were estimated for the 2000 Tottori and the 2001 Geiyo earthquakes, respectively. Then site effects were added to the mean predicted I_{JMA} values using the station factors of the K-NET stations (Shabestari and Yamazaki, 1999). The distributions of the observed I_{JMA} with respect to the values estimated using the empirical attenuation relation are plotted in Fig. 6. A relatively good agreement between the observed values and the I_{JMA} estimated using the empirical attenuation relation for the K-NET sites (Shabestari and Yamazaki, 1999) is observed for both events. However, it should be noted that the site factors of the K-NET may not explain a nonlinear behavior of surface soil layers at some stations. The correlation between the observed and the estimated I_{JMA} values is good for the 2000 Tottori earthquake (Fig. 6a). The 2001 Geiyo earthquake

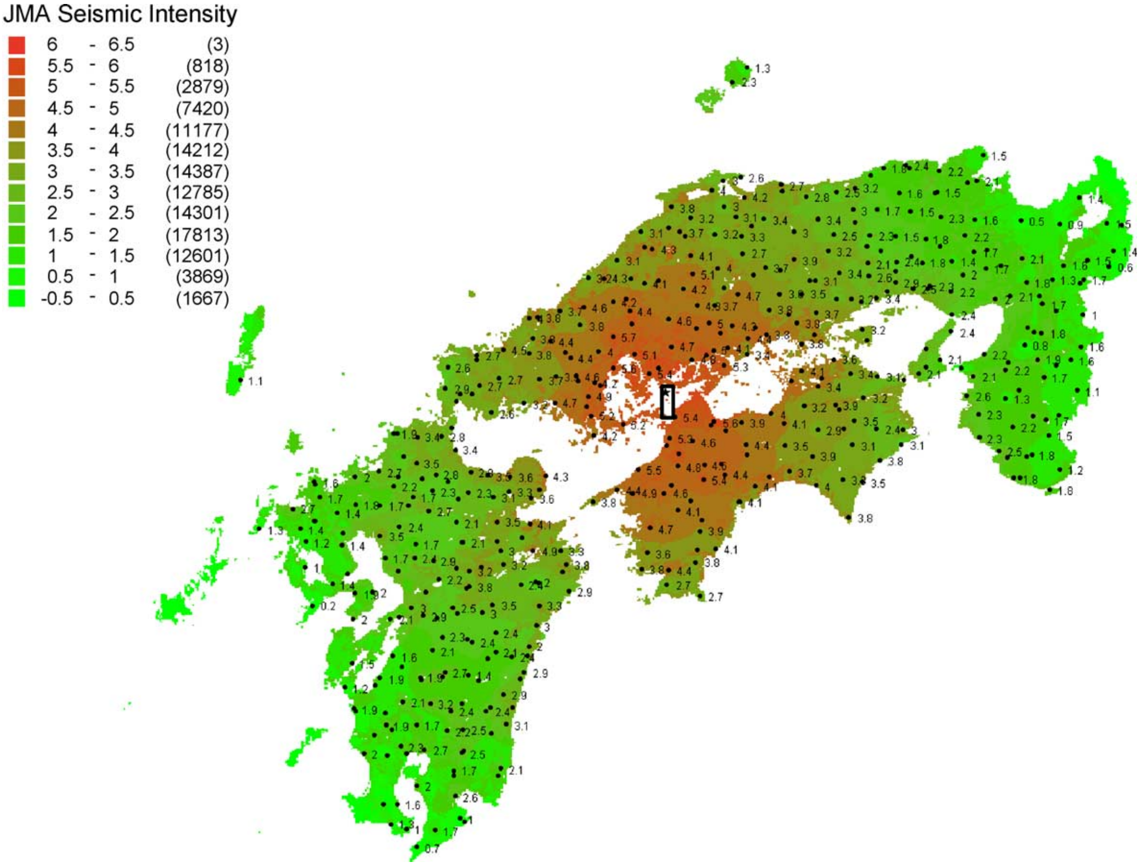

Fig. 5. GIS-based spatial distribution of the I_{JMA}, the epicenter (star), and the surface projection (thick line) of the fault plane for the 2001 Geiyo earthquake. The result is shown for 1×1 km pixels of the DNLI. Plotted values are observed ones. To view this figure in colour, please see the online version of the paper.

comparison indicates that the empirical relation underestimates the I_{JMA} for intermediate-to-large values (Fig. 6b). Again, individually constructing an attenuation relationship for each event does appear to reduce the uncertainty of the inter-event component and may represent more realistic regional attenuation characteristics.

4.2. Verification of the proposed method using the JMA strong motion network

In Japan, the JMA developed the nationwide seismic instrumentation and earthquake information broadcasting system. Since 1996, the JMA has deployed over 500 new JMA-95-type accelerometers throughout Japan (Yamazaki, 1998). We further examined the accuracy of the Yamazaki et al. (2000) method using acceleration records from the JMA network recorded during the 2000 Tottori and the 2001 Geiyo earthquakes. As in earlier, ground motion values were estimated based on Kriging of the K-NET and KiK-net data and the amplification ratio estimated from the DNLI. The estimated PGA, PGV, or I_{JMA} were compared with observed ground motion values recorded by the JMA seismic network stations (Figs. 7 and 8). The general trends of the values estimated for the 2000 Tottori earthquake (see circles in Fig. 7a–c) are well correlated with the observed JMA ones. The agreement between the observed and estimated values is much worse for the 2001 Geiyo earthquake than for the Tottori earthquake. The dense K-NET and KiK-net stations recorded high frequency radiation from the

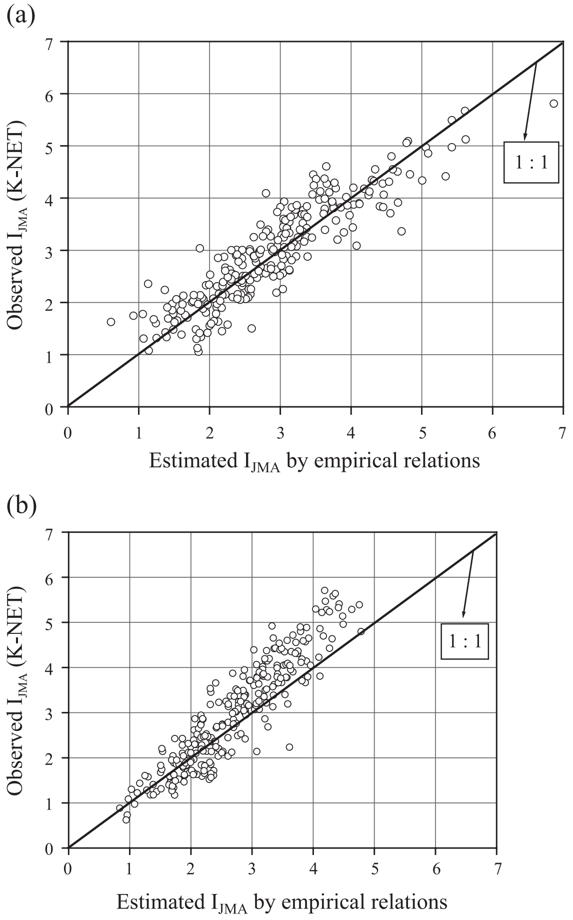

Fig. 6. Comparison of the observed I_{JMA} at K-NET stations and the estimated I_{JMA} by the empirical relations of Shabestari and Yamazaki (1999) considering the site factors of K-NET stations for (a) the 2000 Tottori and (b) the 2001 Geiyo earthquakes.

relatively deep Geiyo earthquake. The amplification ratios employed here for the base-rock conversion may not be adequate for seismic records with rich high-frequency contents.

Scatters from the estimations are observed at some stations (see circles in Figs. 7 and 8). The current Kriging approach matches the observed values at the observation points used for the interpolation, but between the observation points the estimation approaches the trend component as the distance from the observation points becomes large. Site-specific response characteristics of the JMA stations may be the major cause of the scatters. It is well known that

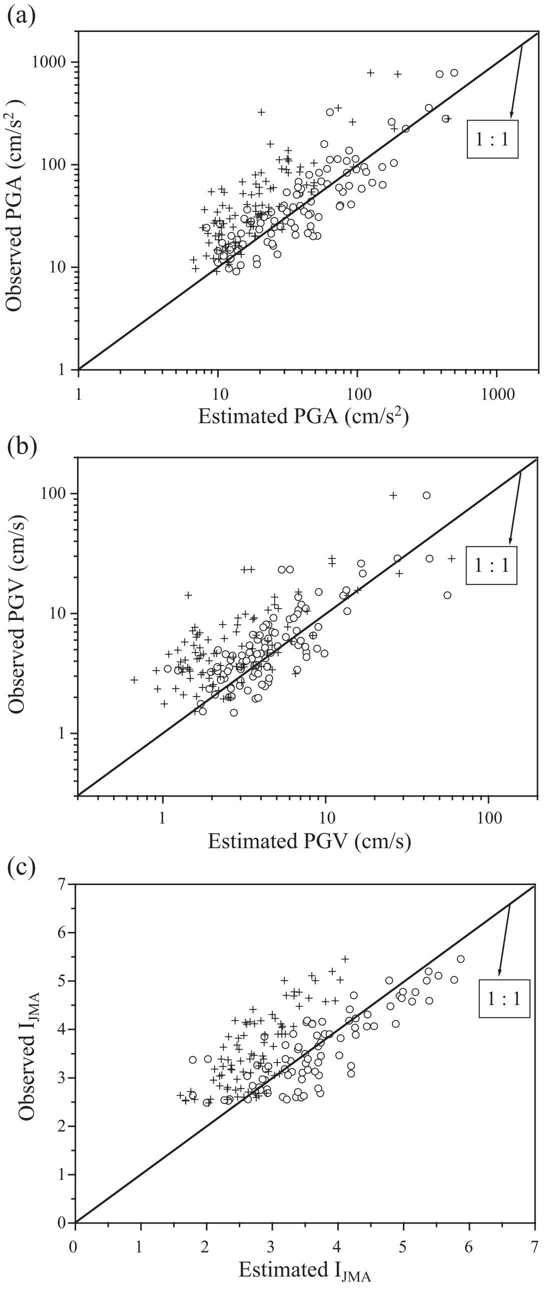

Fig. 7. Comparison of the observed ground motion recorded by the JMA seismic network and the estimated values in the 2000 Tottori earthquake. The circle shows the strong motion indices at the JMA stations estimated by Kriging using K-NET and KiK-net sites and the amplification ratio from the DNLI. The plus sign indicates the estimated indices by the empirical attenuation relation of Shabestari and Yamazaki (1998) with the amplification ratio from the DNLI for (a) PGA, (b) PGV, and (c) I_{JMA}.

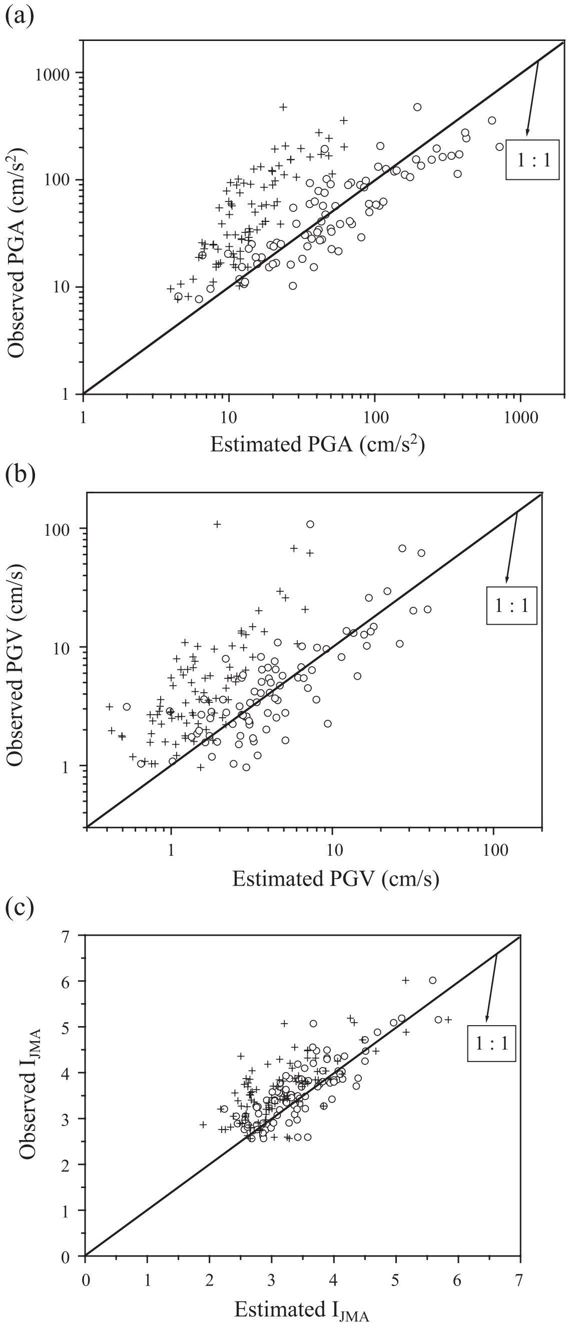

Fig. 8. Distribution of the observed ground motion parameters by the JMA seismic network and the values estimated for the 2001 Geiyo earthquake, for (a) PGA, (b) PGV, and (c) I_{JMA} (for more details refer to the text).

strong motion values are affected by local soil conditions and topography. It may be difficult to reduce the scatter in the data without knowing detailed site response characteristics.

Figs. 7 and 8 (plus sign) support an inference that the use of an attenuation relation for each earthquake as the trend component in Kriging improves the accuracy of estimated ground motion parameters significantly, compared with the straightforward application of a general attenuation relation. For some earthquakes, like the Geiyo earthquake, a systematic difference from the mean attenuation relation exists. In such cases, the development of an attenuation relation for an individual event reduces the intra-event variability.

The accuracy of the GIS-based amplification ratios using the DNLI can be improved using even more comprehensive strong ground motion networks and correlating the station factors with a standardized ground-condition map (e.g., Wakamatsu et al., 2001).

5. Conclusions

This study was intended to demonstrate the accuracy and applicability of nationwide GIS-based amplification ratios for PGA, PGV, and I_{JMA}, as recently proposed by Yamazaki et al. (2000) for Japan. We selected strong ground motion records of the 2000 Tottori-ken Seibu and the 2001 Geiyo earthquakes from the K-NET and KiK-net strong motion networks. In order to reduce site amplification effects, we estimated the spatial distribution of strong motion values at base-rock level using a simple Kriging method that introduced an attenuation relationship as a trend component. Multiplying these estimated values by the amplification ratios across 1×1 km mesh of the DNLI yielded spatial distributions for those parameters at the ground surface. Relatively good correlations between the estimated and recorded ground motion parameters at the JMA seismic stations were observed for both earthquakes. The proposed approach removed inter-event variability of strong motion indices by introducing an attenuation relation for each event, and intra-event variability was considered as the amplification factor, which was linked with the geologic and topographic conditions in the DNLI. Hence, the proposed method can be used to estimate strong motion distributions with reasonable accuracy, leading to early improved earthquake damage assessment in Japan.

References

Abrahamson, N.A., Shedlock, K.M., 1997. Some comparisons between recent ground-motion relations. Seismological Research Letters 68 (1), 9–23.

Aki, K., 1957. Space and time spectra of stationary stochastic waves with special reference to microtremors. Bulletin of the Seismological Society of America 35, 415–456.

Aki, K., 1988. Local site effects on strong ground motion. Proc. of Earthquake Engineering and Soil Dynamics II. GT Div/ASCE, Utah, pp. 103–155.

Aki, K., Chouet, B., 1975. Origin of coda waves: source, attenuation, and scattering effects. Journal of Geophysical Research 80, 3322–3342.

Anderson, J.G., Lee, Y., Zeng, Y., Day, S., 1996. Control of strong motion by the upper 30 meters. Bulletin of the Seismological Society of America 86 (6), 1749–1759.

Bard, P.-Y., 1998. Microtremor measurements: a tool for site effect estimation. Proc. of the 2nd Int. Symp. on Effects of Surface Geology on Seismic Motion vol. 3. ESG 98, Yokohama, Japan, pp. 1251–1282.

Borcherdt, R.D., 1970. Effects of local geology on ground motion near San Francisco Bay. Bulletin of the Seismological Society of America 60, 29–61.

Borcherdt, R.D., 1994. Estimates of site-dependent response spectra for design: methodology and justification. Earthquake Spectra 10 (4), 617–653.

Campbell, K.W., 1985. Strong ground motion attenuation relationships; a ten-year perspective. Earthquake Spectra 1 (4), 759–804.

Chang, T.-Y., Cotton, F., Angelier, J., 2001. Seismic attenuation and peak ground acceleration in Taiwan. Bulletin of the Seismological Society of America 91 (5), 1229–1246.

Deutsch, C.V., Journel, A.G., 1998. Geostatistical software library and user's guide. Applied Geostatistics Series. The Oxford Univ. Press, New York.

Epinosa-Aranda, J., Jimenez, A., Ibarrola, G., Alcantar, F., Aguilar, A., Inostroza, M., Maldonado, S., 1995. Mexico City seismic alert system. Seismological Research Letters 66, 42–53.

Fukushima, Y., Tanaka, T., 1990. A new attenuation relation for peak horizontal acceleration of strong ground motion in Japan. Bulletin of the Seismological Society of America 80 (4), 757–783.

Fukuwa, N., Arakawa, M., Nishizaka, R., 1998. Estimation of site amplification factor using digital national land information. Journal of Structural Engineering 44, 77–84 (in Japanese).

Field, E.H., 2000. Accounting for site effects in probabilistic seismic hazard analyses of Southern California: overview of the SCEC phase III report. Bulletin of the Seismological Society of America 90 (6B), S1–S31.

Heaton, T.H., 1985. A model for a seismic computerized alert network. Science 228, 987–990.

Japan Meteorological Agency, 1996. Note on the JMA seismic intensity. Gyosei, 238 p. (in Japanese).

Journel, A.G., Rossi, M., 1989. When do we need a trend model in kriging. Mathematical Geology 21 (7), 715–739.

Joyner, W.B., Boore, D.M., 1981. Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley California earthquake. Bulletin of the Seismological Society of America 71, 2011–2038.

Kanamori, H., Hauksson, E., Heaton, T., 1997. Real-time seismology and earthquake hazard mitigation. Nature 390, 461–464.

Katayama, T., Sato, N., Saito, K., 1988. SI-sensor for the identification of destructive earthquake ground motion. Proc. of the 9th World Conference on Earthquake Engineering, Tokyo-Kyoto, Japan, vol. VII, pp. 667–672.

Kinoshita, S., 1998. Kyoshin Net (K-NET). Seismological Research Letters 69 (4), 309–332.

Matsuoka, M., Midorikawa, S., 1995. GIS-based integrated seismic hazard mapping for a large metropolitan area. Proceedings of the 5th International Conference on Seismic Zonation vol. 2. AFPS and EERI, Chicago, IL, pp. 1334–1341.

Molas, G.L., Yamazaki, F., 1995. Attenuation of earthquake ground motion in Japan including deep focus event. Bulletin of the Seismological Society of America 85 (5), 1343–1358.

Nakamura, Y., 1989. A method for dynamic characteristics estimation of subsurface using microtremor on ground surface. Quarterly Reports of Railway Technical Research Institute 30, 25–33.

Nakamura, Y., 1996. Research and development of intelligent earthquake disaster prevention systems UrEDAS and HERAS. Journal of Structural Mechanics and Earthquake Engineering, JSCE 537, 1–33 (in Japanese).

Okada, H.T., Matsushima, S., Hidaka, E., 1987. Comparisons of spatial autocorrelation method and frequency-wave number spectral method of estimating the phase velocity of Rayleigh waves in long-period microtremors. Geophysical Bulletin of Hokkaido University 49, 53–62.

Shabestari, T.K., Yamazaki, F., 1998. Attenuation of JMA seismic intensity using recent JMA records. Proceedings of the 10th Japan Earthquake Engineering Symposium vol. 1. Sponsored by Architectural Institute of Japan, Tokyo, pp. 529–534.

Shabestari, T.K., Yamazaki, F., 1999. Attenuation relation of strong ground motion indices using K-NET records. The 25th Japan Society of Civil Engineering, Earthquake Engineering Symposium, Tokyo, vol. 1, pp. 137–140.

Shabestari, T.K., Yamazaki, F., 2001. A proposal of instrumental seismic intensity scale compatible with the MMI evaluated from three-component acceleration records. Earthquake Spectra 17 (4), 711–723.

Shimizu, Y., Watanabe, A., Koganemaru, K., Nakayama, W., Yamazaki, F., 2000. Super High-Density Realtime Disaster Mitigation System, 12th World Conference on Earthquake Engineering, Auckland, New Zealand, p. 7. CD-ROM.

Tinsley, J.C., Fumal, T.E., 1985. Mapping quaternary sedimentary deposits for aerial variations in shaking response, evaluating earthquake hazards in the Los Angeles region: an earth science perspective. J.I. Ziony, U.S. Geological Survey Professional Paper 1360, 101–125.

Tong, H., Yamazaki, F., 1996. Relationship between ground motion indices and new JMA seismic intensity. Seisan-Kenkyu 48 (11), 65–68. (in Japanese).

Tsujiura, M., 1978. Spectral analysis of coda waves from local earthquakes. Bulletin of the Earthquake Research Institute, University of Tokyo 53, 1–48.

Wakamatsu, K., Matsuoka, M., Kubo, S., Sugiura, M., Hasegawa, K., 2001. Development of a nationwide GIS-based ground-condition map for disaster-mitigation systems. In: Otani, S., Sozen, M.A. (Eds.), Proc. of U.S.-Japan Cooperative Research on Urban Earthquake Disaster Mitigation, Seattle, Washington, pp. 146–151.

Wald, D.J., Dengler, L.A., Dewey, J.W., 1999a. Utilization of the Internet for rapid community intensity maps. Seismological Research Letters 70 (6), 680–697.

Wald, D.J., Quitoriano, V., Heaton, T.H., Kanamori, H., Scrivner, C.W., Worden, C.B., 1999b. TriNet "ShakeMaps": rapid generation of peak ground motion and intensity maps for earthquakes in southern California. Earthquake Spectra 15 (3), 537–555.

Wills, C.J., Petersen, M., Bryant, W.A., Reichle, M., Saucedo, G.J., Tan, S., Taylor, G., Treiman, J., 2000. A site-conditions map for California based on geology and shear-wave velocity. Bulletin of the Seismological Society of America 90 (6B), S187–S208.

Wu, Y.-M., Shin, T.-C., Chang, C.-H., 2001. Near real-time mapping of peak ground acceleration and peak ground velocity following a strong earthquake. Bulletin of the Seismological Society of America 91 (5), 1218–1228.

Yagi, Y., Kikuchi, M., 2000. Source rupture process of the October 6, 2000 Tottori-ken Seibu earthquake. http://wwweic.eri.u-tokyo.ac.jp/yuji/tottori/.

Yagi, Y., Kikuchi, M., 2001. Source rupture process of the March 24, 2001 Geiyo earthquake. http://wwweic.eri.u-tokyo.ac.jp/yuji/Aki-nada/.

Yamazaki, F., 1998. Real-time earthquake disaster mitigation system in Japan. Seismology and Earthquake Engineering in Japan. Property and Casualty Insurance Rating Organization of Japan, Tokyo, pp. 133–149.

Yamazaki, F., 2001. Seismic monitoring and early damage assessment system in Japan, Earthquake Engineering and Structural Dynamics, Prog. Struct. Eng. Mater. 3, 66–75.

Yamazaki, F., Noda, S., Meguro, K., 1998. Developments of early earthquake damage assessment systems in Japan. Proc. of 7th International Conference on Structural Safety and Reliability. (ICOSSAR '97). Balkema, Rotterdam, The Netherlands, pp. 1573–1580.

Yamazaki, F., Onishi, J., Tayama, S., 1999. Earthquake damage assessment of expressway structures in Japan. Proc. of Asian-Pacific Symp. on Structural Reliability and its Applications. (APSSRA), National Center for Research on Earthquake Engineering, Taipei, Taiwan, pp. 205–214.

Yamazaki, F., Wakamatsu, K., Onishi, J., Shabestari, K.T., 2000. Relationship between geomorphological land classification and soil amplification ratio based on JMA strong motion records. Journal of Soil Dynamics and Earthquake Engineering 19, 41–53.