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PREDICTION OF AVERAGE SHEAR-WAVE VELOCITY FOR GROUND SHAKING MAPPING USING THE DIGITAL NATIONAL LAND INFORMATION OF JAPAN

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SUMMARY

The objective of this study is to generate a nationwide map of the average shear-wave velocity in the upper 30m of the ground (AVS) from geomorphological data in order to create a more reliable ground-shaking map for all over Japan. The integrated database, which consists of the AVS data obtained from borehole logs at 1,785 sites and the corresponding geomorphological data retrieved from the Digital National Land Information (DNLI) covering all over Japan, is constructed. Using the database, the relations between the AVS and the geomorphological condition are compared for three regions divided by major tectonic lines. A statistical hypothesis test for the relations reveals that the AVS in the central part of Japan tends to be lower than those in the northeast and southwest parts of Japan on several geomorphological conditions such as alluvial fan, delta and back marsh. Such regional difference of the AVS for each geomorphological condition is incorporated in a method for estimating the site amplification factor from the geomorphological data in the DNLI through the AVS. For comparison, the site amplification factor (ARV) for entire region of Japan is computed using the method proposed herein and existing methods. Consequently, the proposed method considering the regionality of the AVS can predict the AVS and the ARV in all the parts of Japan more accurately than the existing methods.

INTRODUCTION

After the 1995 Hyogo-ken Nanbu, Japan earthquake, the occurrence of great inter-plate earthquake along the Suruga and Nankai Troughs with a magnitude of 8 or more is expected in Japan. Such large earthquake will cause devastating damage in wide area of Japan. For predicting the earthquake damage for broad area, the distribution of ground shaking intensity must be evaluated appropriately. Average shear-wave velocity in the upper 30m of the ground (AVS) has been providing good estimates of site amplification factor on ground shaking [1]. Geological and physical properties for a given geomorphological condition strongly correlate with the AVS. These suggest that the site amplification factor can be estimated from geomorphological information through the AVS.

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In the United States, the distribution of the AVS for large area is obtained by assigning the typical AVS value for each surficial geologic unit [2]. In Japan, using the soil data obtained in the Kanto area (a part of central Japan), Matsuoka and Midorikawa [3] developed a simple method for estimating the AVS from geomorphological data. In the method, the geomorphological data is derived from the Digital National Land Information (DNLI) covering all over Japan. Fukuwa *et al.* [4] also proposed a method for predicting the site amplification factor directly from the geomorphological data in the DNLI in Aichi Prefecture (a part of southwest Japan). Since these methods are based on the soil data collected in a certain region of Japan, the applicability of the methods to wider area (e.g., whole area of Japan) has not been fully examined.

The objective of this study is to generate a nationwide map of the AVS from the geomorphological data in the DNLI in order to create a more reliable ground-shaking map covering all over Japan. The database on the AVS data compiled from borehole logs at 1,785 sites together with the geomorphological data retrieved from the DNLI is constructed. Using the database, the regional difference in the relationship between the AVS and the geomorphological condition is examined. The regionality of the AVS for each geomorphological condition is incorporated in a method for estimating the AVS in terms of the geomorphological data in the DNLI.

CONSTRUCTION OF DATABASE ON AVERAGE SHEAR-WAVE VELOCITY AND GEOMORPHOLOGICAL DATA

Matsuoka and Midorikawa [3] proposed a simple method for estimating the AVS from the geomorphological data retrieved from the Digital National Land Information (DNLI) which is an extensive geographical database with a mesh size of about 1km covering all over Japan.

$$\log AVS = a + b \log H + c \log D \tag{1}$$

where AVS is the average shear-wave velocity in the upper 30m of the ground (m/s), H and D is an elevation (m) and a distance from major river (km) in the DNLI, respectively. The regression coefficients a, b and c in Eq. (1) for each geomorphological condition in the DNLI are listed in Table 1. First, in order to construct the database on the AVS, digital shear-wave velocity datasets of K-NET, KiK-net, the Yokohama Dense Strong-Motion Network, Matsuoka and Midorikawa [3], and Fujimoto and Midorikawa

Table 1 Regression coefficients for Eq. (1) after Matsuoka and Midorikawa (1995)

Geomorphological Condition		Regression Coefficient			Number of Data	σ
		a	*b*	*c*		
Mountain		2.87	0	0	3	0.23
Quaternary Volcano		2.25	0.13	0	10	0.16
Hill		2.64	0	0	22	0.17
Gravel Plateau		1.76	0.36	0	12	0.12
Loam Plateau		2.00	0.28	0	95	0.11
Alluvial Fan		1.83	0.36	0	20	0.15
Sand Dune, Sand Bar		2.29	0	0	13	0.13
Valley Plain		2.07	0.15	0	26	0.12
Natural Levee		1.94	0.32	0	18	0.13
Delta, Back Marsh	$D \geq$ 0.5km	2.26	0	0.25	57	0.13
	$D \leq$ 0.5km	2.19	0	0	36	0.12
Developed Land		2.26	0	0	7	0.09
Reclaimed Land, Drained Land		2.23	0	0	132	0.14

a,*b* and *c*: regression coefficients in Eq. (1), *D*: distance from major river (km)

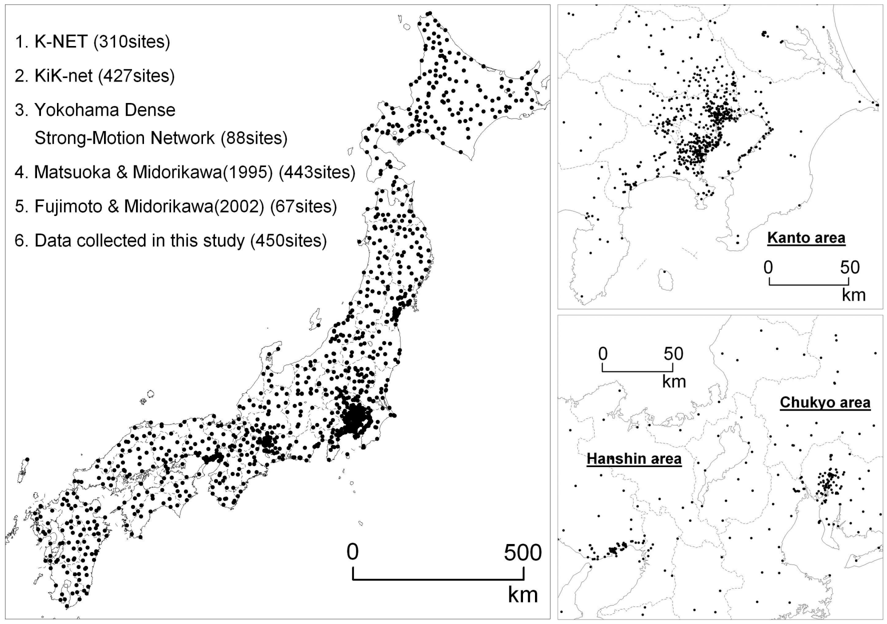


Figure 1 Distribution of database on AVS and geomorphological data

[5] are collected. In order to enrich the amount of the AVS data, the documents on borehole logs at 450 sites are collected throughout Japan, and then digitized. For these data, the AVS is calculated from the shear-wave velocity profile at each site. Then, the AVS data is geographically linked with the corresponding geomorphological data (geomorphological condition, elevation, and distance from major river) in the DNLI by means of GIS technique. Accordingly, the total number of the sites in the database on both the AVS and geomorphlogical data is 1,785. Figure 1 shows the distribution of the sites in the database, which almost covers the whole area of Japan.

REGIONAL DIFFERENCE OF AVERAGE SHEAR-WAVE VELOCITY WITH GEOMORPHOLOGICAL CONDITION

According to the previous studies (e.g., Fujimoto and Midorikawa [5]), the relation between the AVS and

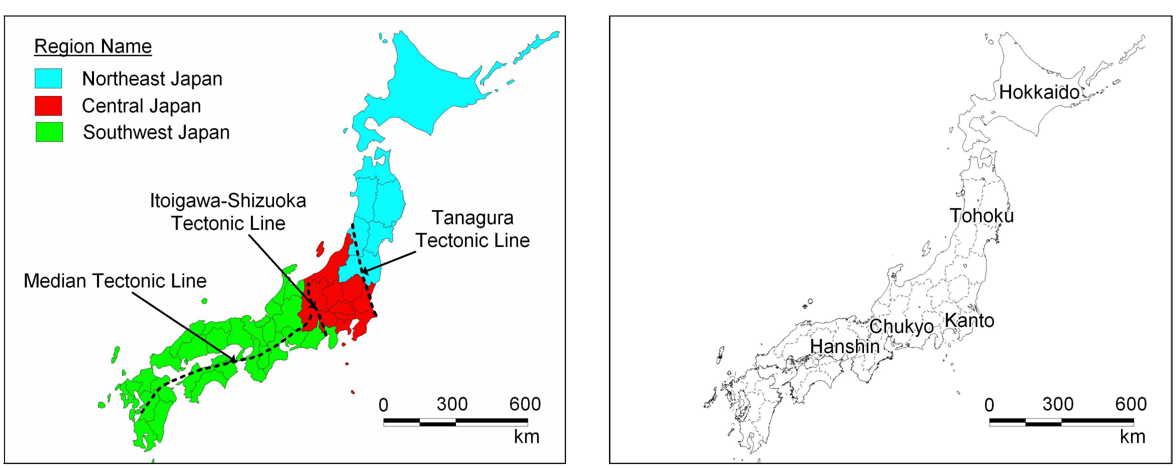


Figure 2 Zoning map based on major tectonic lines (left) and area map (right)

the geomorphological condition in the Kanto area (a part of central Japan) is different from those in the Hanshin and Chukyo areas (parts of southwest Japan)(see Fig. 1). Geological settings in the central Japan and the southwest Japan have changed on the border of Itoigawa-Shizuoka Tectonic Line. This suggests that the AVS on a certain geomorphological condition might vary on the boundary of major tectonic line in Japan. For evaluating the regional difference of the AVS in terms of geomorphological condition, the whole area of Japan is divided broadly into three regions; northeast Japan, central Japan, and southwest Japan. Figure 2 shows the zoning map of Japan on the basis of Itoigawa-Shizuoka and Tanagura Tectonic Lines.

The relations of the AVS in terms of the elevation for the three regions are plotted by solid circles in

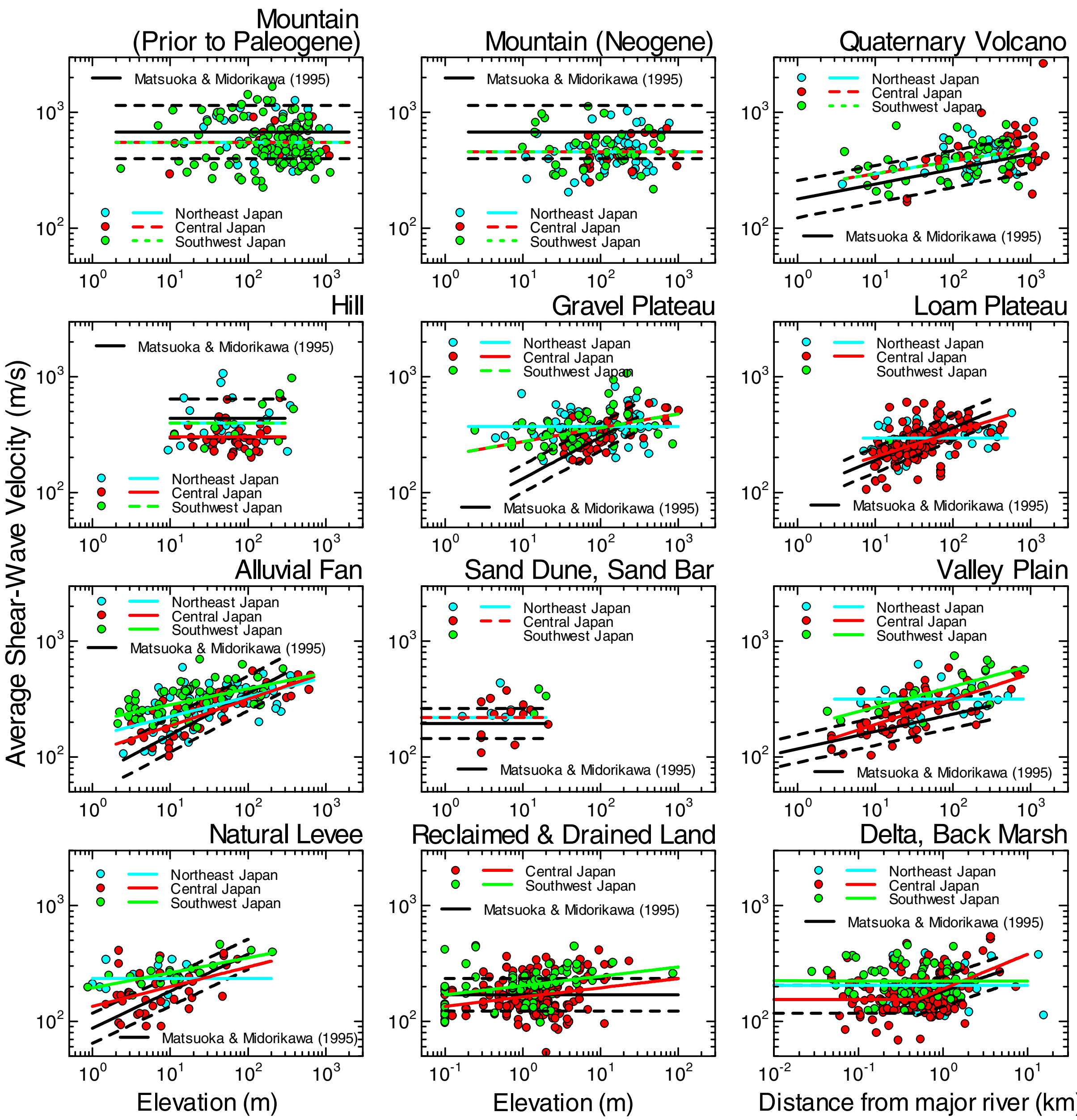


Figure 3 Relation between AVS and elevation for each geomorphological condition
[Relation between AVS and distance from major river is shown for “Delta and Back Marsh”]

Figure 3. The regression line derived from the soil data obtained in the Kanto area (a part of the central Japan) [3] is also shown by black line. As shown in Fig. 3, the regression line (black line) fairly agrees with the relation for the central Japan (red circle) however it differs from the relation for the northeast and southwest regions.

Such regional difference of the AVS for each geomorphological condition is examined by assessing whether 1) a population mean of the relation in one region significantly different from that in another region, and 2) a slope of the relation in one region significantly differs from that in another region. Thus, by testing statistical hypotheses for the population mean and the slope for each combination from the three regions, the significant difference of the AVS in the relations is evaluated. A statistical hypothesis test reveals that the AVSs on mountain (prior to Paleogene), mountain (Neogene), and Quaternary volcano are nearly the same in the three regions. On the other hand, the AVS in the central Japan tends to be lower than those in the northeast and southwest parts of Japan on several geomorphological conditions such as alluvial fan, delta and back marsh, suggesting the sedimentary deposit in the central part of Japan is softer relative to the other parts. This is possibly resulted from a particular geomorphological environment in the central Japan in which the soft subsoil is easily formed because of Quaternary subsidence.

ESTIMATION OF AVERAGE SHEAR-WAVE VELOCITY FOR GROUND-SHAKING MAP THROUGHOUT JAPAN

To obtain a more reliable ground-shaking map covering all over Japan, the regional differences of the AVS in terms of the geomorphological condition are incorporated into Eq. (1). For the geomorphological conditions with which the regional difference is not found (mountain (prior to Paleogene), mountain (Neogene), and Quaternary volcano), the regression coefficient is determined from which the data obtained from the three regions are merged, whereas the regression coefficient is calculated for each region as to the other geomorphological conditions. The regression coefficients in consideration of the presence or absence of the regionality are presented in Table 2. In Fig. 3, the regression lines considering the regionality of the AVS are overlaid by blue, red, and green lines for the northeast Japan, the central Japan, and the southwest Japan, respectively.

Table 2 Regression coefficients for Eq. (1) proposed in this study

Geomorphological Condition	Region	Regression Coefficient			Number of Data	σ
		a	*b*	*c*		
Mountain (Prior to Paleogene)	N				33	
	C	2.74	0	0	17	0.18
	S				131	
Mountain (Neogene)	N				53	
	C	2.66	0	0	20	0.15
	S				39	
Quaternary Volcano	N				27	
	C	2.36	0.11	0	30	0.16
	S				47	
Hill	N	2.60	0	0	22	0.19
	C	2.48	0	0	36	0.12
	S	2.60	0	0	11	0.21
Gravel Plateau	N	2.57	0	0	55	0.14
	C	2.32	0.12	0	49	0.13
	S				53	
Loam Plateau	N	2.47	0	0	34	0.12
	C	2.10	0.21	0	129	0.13
	S	(2.10)	(0.21)	(0)	1	—
Alluvial Fan	N	2.18	0.17	0	58	0.15
	C	2.04	0.23	0	40	0.12
	S	2.31	0.14	0	69	0.11

Geomorphological Condition	Region	Regression Coefficient			Number of Data	σ
		a	*b*	*c*		
Sand Dune, Sand Bar	N	2.34	0	0	6	0.15
	C				16	
	S	(2.34)	(0)	(0)	3	—
Valley Plain	N	2.50	0	0	20	0.13
	C	2.06	0.22	0	71	0.13
	S	2.25	0.18	0	23	0.12
Natural Levee	N	2.37	0	0	10	0.14
	C	2.13	0.17	0	42	0.16
	S	2.29	0.13	0	24	0.07
Delta,	N	2.31	0	0	24	0.18
Back Marsh	S	2.35	0	0	67	0.13
(D＞0.5km)	C	2.28	0	0.30	103	0.14
(D≦0.5km)	C	2.19	0	0	73	0.15
Developed Land	N	(2.10)	(0.20)	(0)	4	—
	C	2.10	0.20	0	43	0.11
	S	2.50	0	0	14	0.23
Reclaimed Land Drained Land	N	(2.21)	(0.08)	(0)	0	—
	C	2.21	0.08	0	207	0.14
	S	2.31	0.08	0	81	0.14

N: Northeast Japan, C: Central Japan, S: Southwest Japan
a,b and *c*: regression coefficients in Eq. (1), *D*: distance from major river (km)

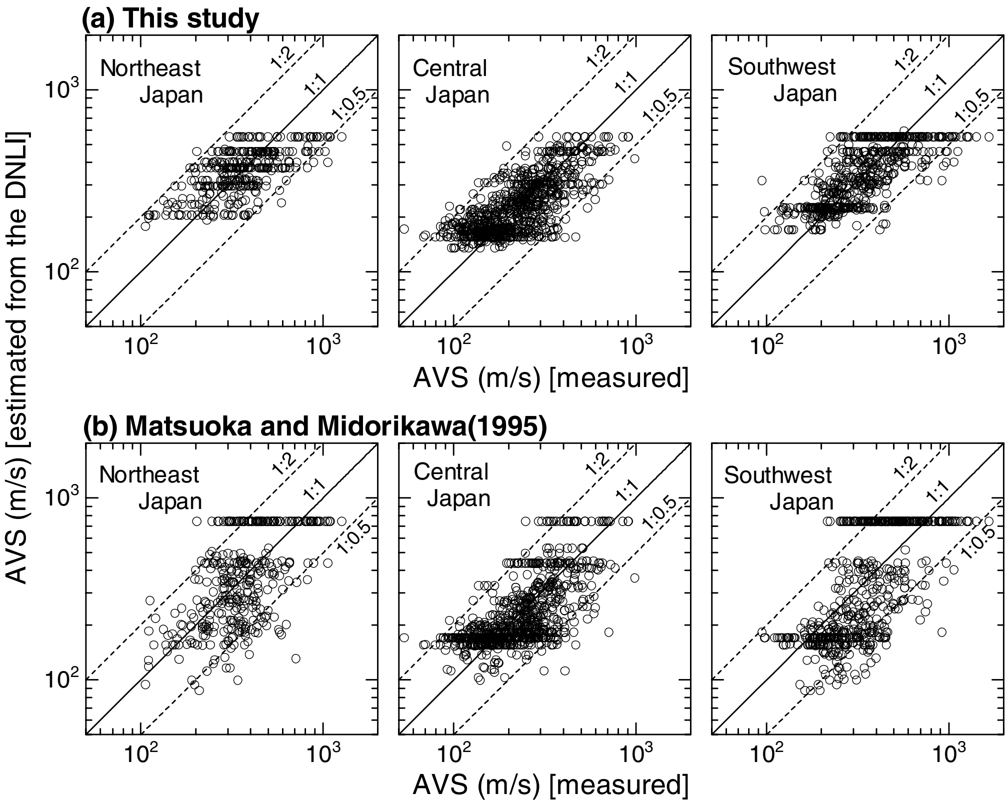


Figure 4 Comparison between measured and estimated AVSs

In order to evaluate the accuracy of the AVS estimated from the method proposed herein, the relation of the AVS between the measured values and the estimated values from the regression coefficient in Table 2 is examined (see Fig. 4 (a)). As a matter of course, the results coincide with each other. For comparison, the relation for the AVS estimated from the regression coefficients in Table 1 [3] is also shown in Fig. 4 (b). The estimates show relatively good agreement with measured values in the central Japan while the discrepancies are found in the northeast Japan and the southwest Japan.

This study finally aims at evaluating the distribution of site amplification throughout Japan, the accuracy of the site amplification factor estimated from the AVS is also examined. Site amplification factor is evaluated by substituting the AVS derived from Eq. (1) into the following equation [6].

$$\log ARV = 1.83 - 0.66 \log AVS \pm 0.16 \quad (100 < AVS < 1500) \tag{2}$$

where ARV is the site amplification factor for peak ground velocity. Although this equation is derived from the strong-motion records during the 1987 Chiba-ken-toho-oki, Japan earthquake, the applicability of the equation to the records with higher amplitude during the 2001 Geiyo, Japan earthquake is confirmed [7]. The ARVs for entire region of Japan are computed using the method proposed herein and the existing methods by Matsuoka and Midorikawa [3] and Fukuwa *et al.* [4].

In Fig. 5, the horizontal and vertical axes indicate the ARVs derived from Eq. (2) by substituting the measured AVS and the estimated AVS from Eq. (1), respectively. In Fig. 5 (a), the ARV estimated from the method developed by Matsuoka and Midorikawa [3] shows relatively good agreement with the

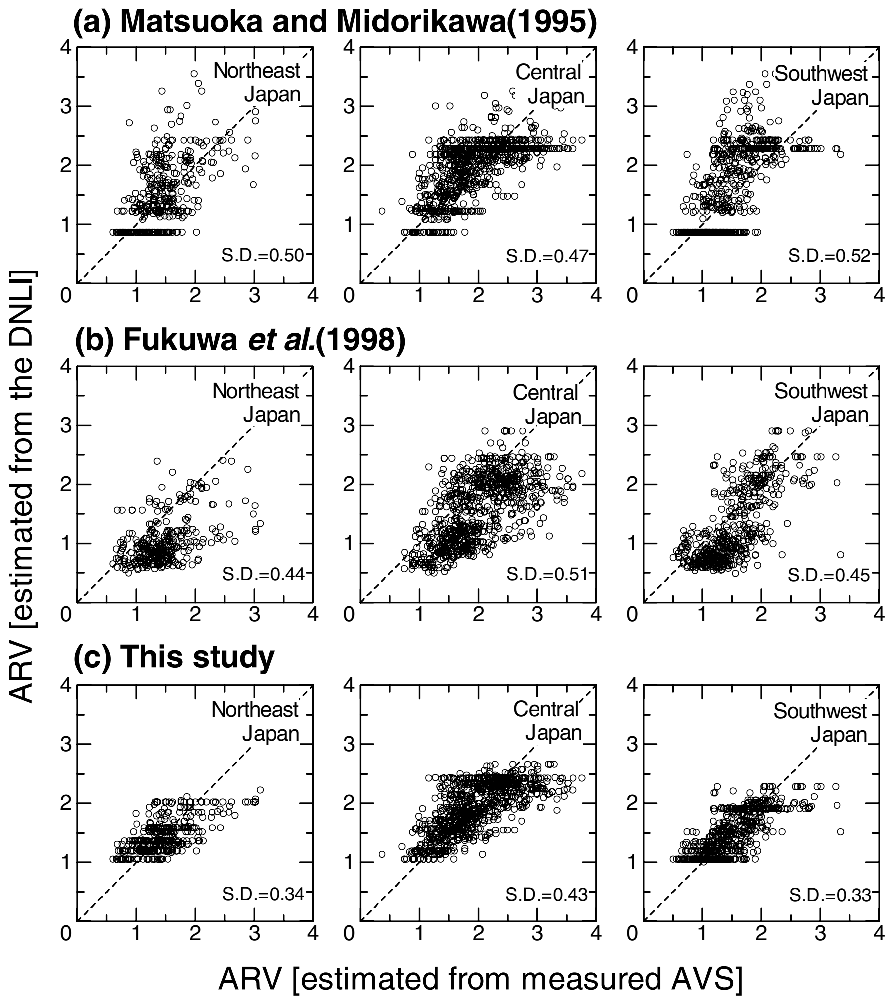


Figure 5 Comparison of ARV estimated from measured AVS with ARV estimated from the DNIL

measured values in the central Japan where the soil data was used in the method however the relations show less agreement in the northeast and southwest parts of Japan. A similar tendency is observed in the results from the method proposed by Fukuwa *et al.* [4] (see Fig. 5 (b)). On the contrary, when applying the method proposed in this study, the results show good one-to-one relationship in all the three regions (see Fig. 5 (c)). Using Equations (1) and (2), the method proposed herein can predict the ARV throughout Japan more accurately than the existing methods with an accuracy of approximately $\pm 50\%$.

Figures 6 (a) and (b) show the distributions of the ARV and the AVS estimated from the method proposed in this study, respectively. The geomorphological condition map is also shown in Fig. 6 (c). In the mountain area, the ARVs in the northeast and central parts of Japan are somewhat larger than that in the southwest Japan. In the plain area, the ARV in the central Japan shows higher value compared with those in the northeast and southwest parts. Figure 6 (d) shows the ratio of the AVS estimated from Matsuoka and Midorikawa [3] to that from this study. The ratio exceeding 100% indicates that the AVS estimated from this study is smaller than that from Matsuoka and Midorikawa [3]. As illustrated in Fig. 6 (d), the AVS estimated from Matsuoka and Midorikawa [3] shows higher values in the mountain area of all the parts of Japan. In the plain areas, the AVS estimated from Matsuoka and Midorikawa [3] shows good agreement in the central Japan while the AVS is underestimated in the northeast and southwest parts.

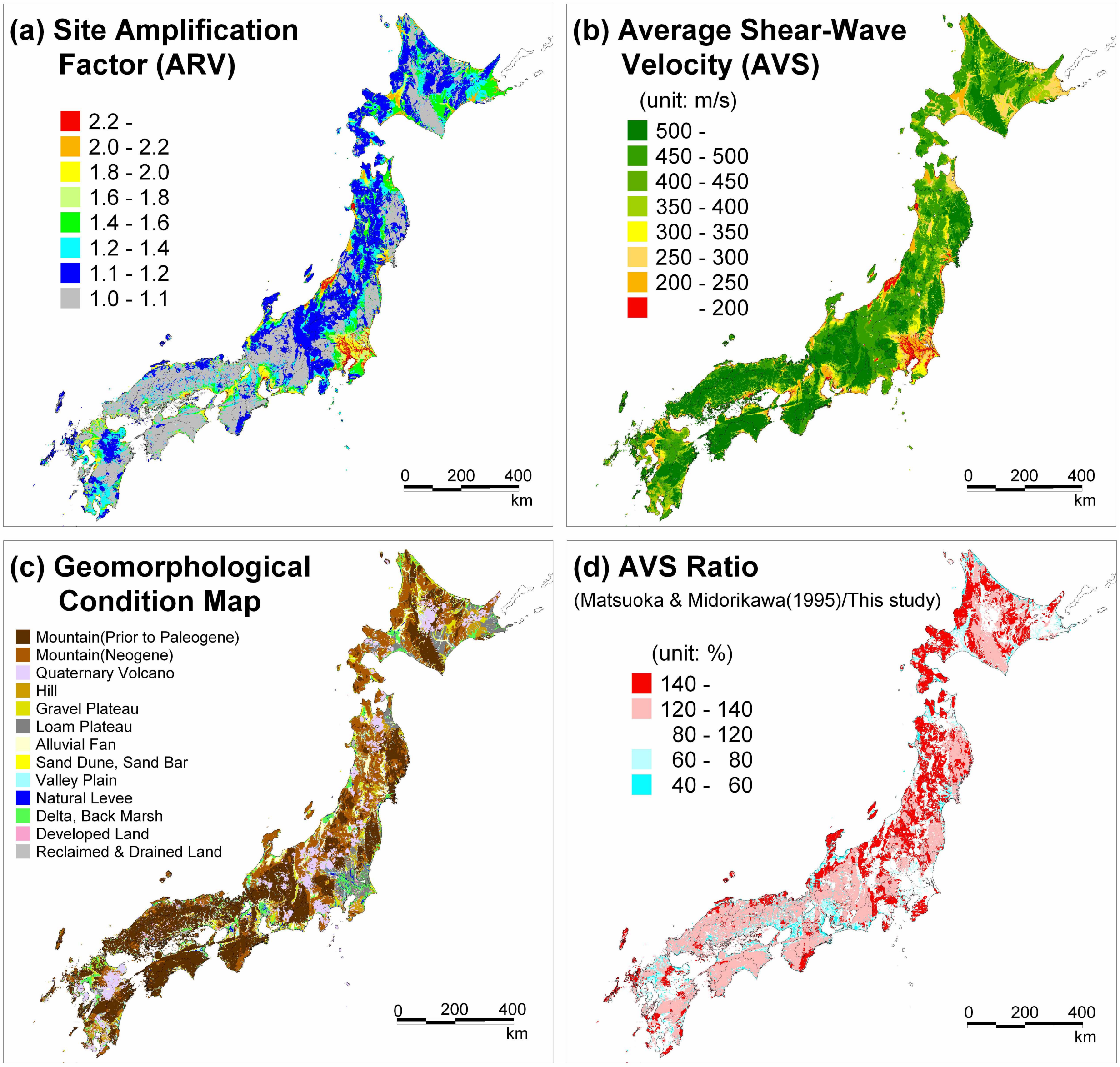
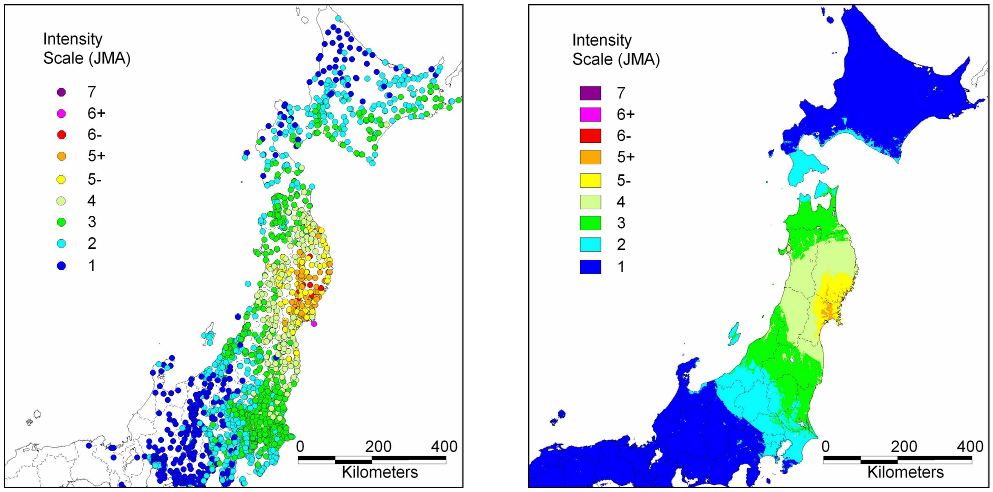


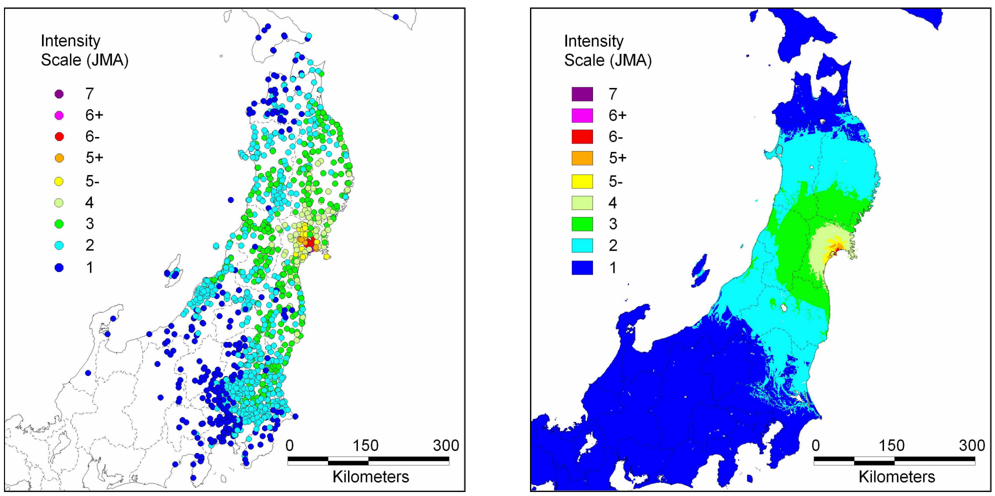
Figure 6 Distributions of ARV and AVS

[(a) site amplification factor (ARV), (b) average shear-wave velocity (AVS), (c) geomorphological condition, (d) AVS ratio (Matsuoka and Midorikawa(1995)/This study)]

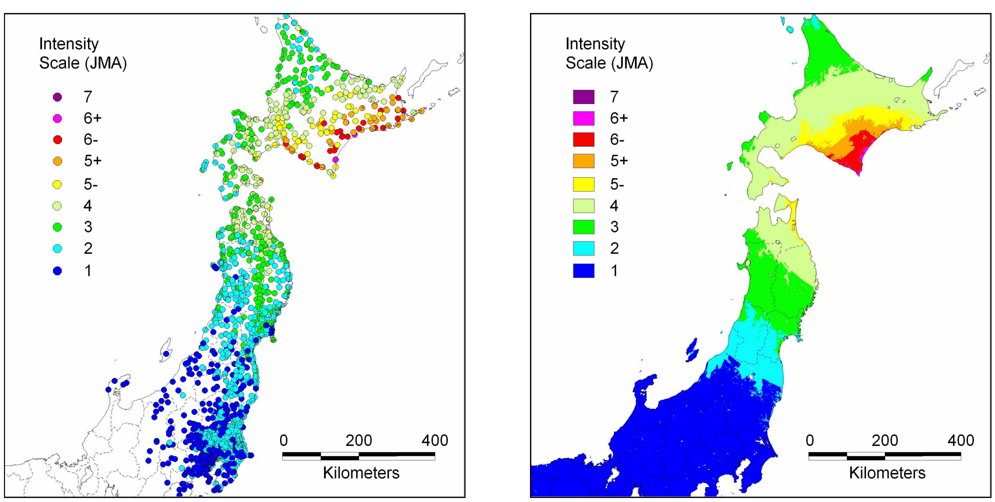
In the year 2003, the three large earthquakes, i.e., the Miyagi-ken-oki earthquake (M_W7.0) on May 26, the Miyagi-ken-hokubu earthquake (M_W6.0) on July 26, and the Tokachi-oki earthquake (M_W8.0) on September 26, were occurred in Japan. In order to examine the applicability of the method proposed by the authors to wider area of Japan, the distributions of the seismic intensity calculated from the method are compared with the actual isoseismal map for the earthquakes. The peak velocity on engineering bedrock with a shear-wave velocity of about 600 m/s is computed for the earthquakes using the empirical attenuation relationship [8]. By multiplying the peak velocity on engineering bedrock and the ARV estimated from the proposed method, peak ground velocity is obtained. Then, the peak ground velocity is converted to the seismic intensity in the Japan Meteorological Agency (JMA) scale by employing the empirical relationship between the seismic intensity and ground motion parameters [9]



(a) Miyagi-ken-oki earthquake



(b) Miyagi-ken-hokubu earthquake



(c) Tokachi-oki earthquake

Figure 7 Observed and computed seismic intensity map

[Left: observed map, Right: computed map]

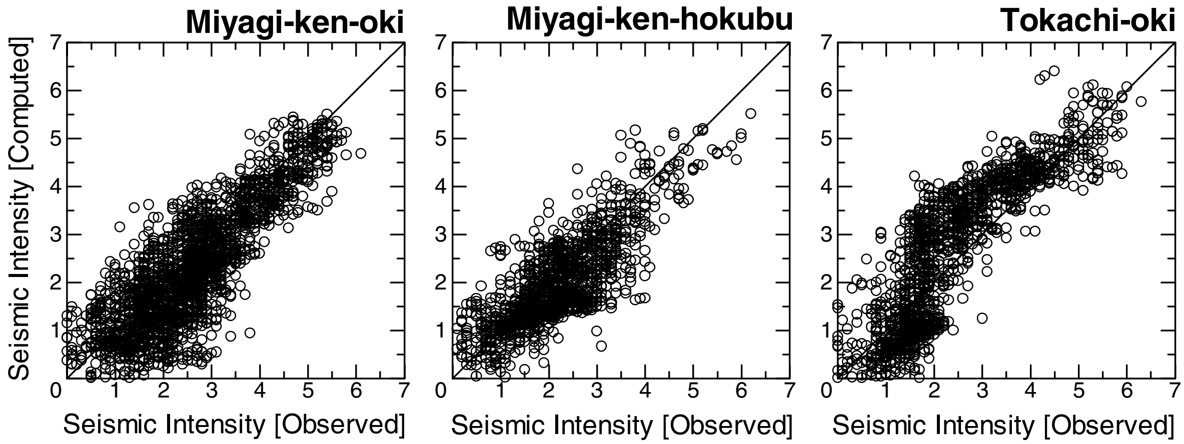


Figure 8 Comparison of seismic intensity between observed and computed values

Figures 7 (a), (b) and (c) show the observed and computed seismic intensity maps for the Miyagi-ken-oki earthquake, the Miyagi-ken-hokubu earthquake, and the Tokachi-oki earthquake, respectively. In the observed map, the strong-motion records obtained from K-NET, KiK-net, JMA, and the local governments are utilized. Figure 8 represents the comparison of the seismic intensity between the observed and computed values. A comparison for the Miyagi-ken-oki earthquake shows that the computed map matches with the observed map in large area except for the southern part of Hokkaido (refer to “area map” in Fig. 2). In the case of the Miyagi-ken-hokubu earthquake, the computations show relatively good agreement with the observations from Hokkaido to Kanto area. As for the Tokachi-oki earthquake, the computed seismic intensity in the southern part of Hokkaido is in accord with the observed one however the computation tends to be greater than the observation in the northern part of Hokkaido and Tohoku areas.

CONCLUSIONS

In order to create a more reliable ground-shaking map covering all over Japan, a nationwide map of the average shear-wave velocity of the ground (AVS) is estimated from the geomorphological data in the Digital National Land Information (DNLI). The database on the AVS data compiled from borehole logs at 1,785 sites together with the geomorphological data retrieved from the DNLI is constructed. Using the database, the regionality of the relation between the AVS and the geomorphological data is examined. A statistical hypothesis test for the relations reveals that the AVS in the central part of Japan tends to be lower than those in the northeast and southwest parts on several geomorphological conditions such as alluvial fan, delta and back marsh. Such regional difference of the AVS for each geomorphological condition is incorporated in a method for estimating the site amplification factor (ARV) from the AVS in terms of the geomorphological data in the DNLI. For comparison, the ARV for entire region of Japan is computed using the method proposed in this study and the existing methods. The proposed method, which considers the regional difference of the AVS, can predict the AVS and the ARV in all the parts of Japan more accurately than the existing methods. Using the distribution of the ARV estimated from the proposed method and empirical attenuation relationship, the seismic intensity maps for three large earthquakes occurred in 2003 are computed. A comparison between the computed and actual observed seismic intensities shows relatively good agreement.

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