EMPIRICAL ESTIMATION OF LONG-PERIOD (1-10 SEC.) EARTHQUAKE GROUND MOTION ON HARD ROCKS

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ABSTRACT :

As a basic approach to understand long-period (1-10 sec.) ground motion (LPGM), we obtained a spectral LPGM attenuation model on hard rocks using the downhole data registered by the KiK-net (NIED) hard rock sites of which S-wave velocity exceeds 2.0 km/s. The data from earthquakes of larger magnitudes than 5.9 were used. Next, we estimated the shakeability at arbitrary sites using K-NET and KiK-net surface recordings by taking spectral ratio to the proposed model for hard rocks. A very strong spatial variation of shakeability was found in and around large basins. The shakeability at thick sediment sites exceeding more than 10 times of rock sites is not rare and it also depends strongly on period. The obtained shakeability may be useful for assessing seismic safety of long-period structures. To use the average with one standard deviation is recommended as a standard predictive model for hard rock sites. In addition, site amplifications by including one standard deviation with the average are recommended for safer consideration of LPGM.

KEYWORDS : Long-period ground motion, empirical predictive model, hard rock, shakeability

1. INTRODUCTION

To assess the long-period (1-10 sec.) ground motion (LPGM) has become a critical issue associated with a recent rapid increase of tall buildings, base-isolated structures, long-span bridges, large storage oil-tanks and so on. Recent Tokachi-oki earthquake of 2003 remind us the importance of LPGM, as we experienced oil sloshing and fire. We know that the essential effects on LPGM are earthquake sources. But site and path effects are also inevitable even for LPGM. The site including path effects to LPGM in land Japan have ever been estimated by Okada and Kagami (1978), Mamula et al. (1984), and Zama (2000). Those results show the strong spatial or regional variation of LPGM. However, these estimated sites or regions are limited at only the observation sites (about 100 sites in whole Japan) of Japan Meteorological Agency (JMA). Recently, Kataoka et al. (2006) obtained statistically the average spectral predictive model using records of many strong motion sites and estimated the relative LPGM shakeability as a function of period.

In order to clearly recognize the shakeability at a site associated with geological / geotechnical data, we first obtain a standard attenuation relation of spectral ground motion on hard rock sites. Next, we estimate shakeability of LPGM at a site by spectral ratio to the standard attenuation model. Predictive models of ground motion on hard rock have been proposed by Takahashi et al. (1998) and Noda et al. (2002), however, these empirical predicting models are limited within a shorter period than 5 sec.

We used the data from the KiK-net (Aoi et al., 2000), that is established by National Research Institute for Earth Science and Disaster Prevention (NIED), by selecting hard rock sites where the S-wave velocity of 2.0 km/s or higher is found at a shallow depth and by choosing the earthquakes of which magnitudes larger than 5.9 (total earthquakes of 18). However, the KiK-net data on hard rock sites are mostly observed at a downhole; therefore, we have to take care of the effects of reflected waves at surface and shallow interfaces. We selected 161 sites among hard rock sites where the spectral ratios between surface and borehole (rock) sites do not exceed a factor of 2 at longer period than 1 second.

Using thus obtained standard model at hard rock sites, ground motions at some thick sediments sites are predicted and compared with the observations.

2. DATA

We determine a standard spectral attenuation against distance of LPGM on hard rock sites, as a first step. Next, we estimate shakeability of LPGM at a site by spectral ratio to the standard attenuation model. We use the KiK-net data from moderately large earthquakes as listed in Table 1 and the locations are shown on a map as shown in Figure 1. These earthquakes were selected taking into account their magnitudes, distribution of sources and depth or fault-types.
The definition of "hard rock site" will be very important. In this study, we defined a hard rock site as that the S-wave velocity at down-hole and / or surface sites based on the geotechnical data of KiK-net exceeds 2.0 km/sec. In addition, we did not use the deep and soft sediment sites that amplification factors (ratio of surface to downhole motions) are larger than a factor of two at longer period than 1 sec., in order to avoid the effects of reflected subsurface layers. In other words, we used the data that could be approximated as free surface motions restricting the frequency range less than 1 Hz. It will be preferable to use the higher velocity of 3.0km/sec, but numbers of those sites decrease rapidly. The number of such defined sites is 161 among about 670 sites of KiK-net, and they are shown in Figure 2. The distribution of those sites cannot be said homogeneous, but it covers roughly whole Japan. Figure 3 shows a histogram of S-wave velocity at hard rock sites used in the present study.

Table 1 Earthquake source parameters used in this study

No.	Origin time (JST)	Long. (deg)	Lat. (deg)	M_{JMA}	M_W	Depth (km)	Region name	Type
1	2000. 07. 15 10: 30	139° 14.50'	34° 25.40'	6.3	6.0	10	NEAR NIIJIMA ISLAND	crustal
2	2000. 10. 06 13: 30	133° 20.94'	35° 16.45'	7.3	6.6	8.96	The Western Tottori Earthquake in 2000	crustal
3	2001. 03. 24 15: 27	132° 41.62'	34° 07.94'	6.7	6.8	46.46	The Geiyo Earthquake in 2001	intra-slab
4	2002. 11. 04 13: 36	131° 52.17'	32° 24.76'	5.9	5.7	35.19	HYUGANADA REGION	inter-plate
5	2003. 02. 19 14: 01	141° 50.83'	44° 07.14'	5.9	5.9	222.25	RUMOI REGION	intra-slab
6	2003. 05. 26 18: 24	141° 39.04'	38° 49.26'	7.1	7.0	72.03	NORTHERN MIYAGI PREF	intra-slab
7	2003. 07. 26 07: 13	141° 10.26'	38° 24.30'	6.4	6.1	11.87	NORTHERN MIYAGI PREF	crustal
8	2003. 09. 26 04: 50	144° 04.71'	41° 46.71'	8.0	7.9	45.07	The Tokachi－oki Earthquake in 2003	inter-plate
9	2004. 09. 05 23: 57	137° 08.48'	33° 08.25'	7.4	7.5	43.54	SE OFF KII PENINSULA	intra-slab
10	2004. 10. 23 17: 56	138° 52.03'	37° 17.55'	6.8	6.6	13.08	The Mid Niigata prefecture Eartquake in 200	crustal
11	2004. 12. 14 14: 56	141° 41.97'	44° 04.60'	6.1	5.7	8.58	RUMOI REGION	crustal
12	2005. 03. 20 10: 53	130° 10.58'	33° 44.35'	7.0	6.6	9.24	NW OFF KYUSHU	crustal
13	2005. 07. 23 16: 34	140° 08.31'	35° 34.90'	6.0	5.9	73.08	CENTRAL CHIBA PREF	inter-plate
14	2005. 08. 16 11: 46	142° 16.67'	38° 08.97'	7.2	7.1	42.04	E OFF MIYAGI PREF	inter-plate
15	2005. 10. 19 20: 44	141° 02.59'	36° 22.90'	6.3	6.3	48.32	E OFF IBARAKI PREF	inter-plate
16	2006. 06. 12 05: 01	131° 24.40'	33° 08.00'	6.2	6.4	146	NORTHERN OITA PREF	intra-slab
17	2007. 03. 25 09: 41	136° 41.10'	37° 13.20'	6.9	6.7	11	The Noto Hanto Earthquake in 2007	crustal
18	2007. 07. 16 10: 13	138° 36.50'	37° 33.40'	6.8	6.6	17	The Niigataken Chuetsu-oki Earthquake in 2	crustal

Remark) Basic data are from JMA and M_W (moment magnitude) determined by F-net (NIED)

3. EMPIRICAL PREDICTIVE MODEL

Body wave far-field spectrum can be represented as,

$$F(f)=\frac{R_{\theta\varphi}\omega^2}{4\pi\rho V_S^3}M_0(f)\frac{1}{X}\cdot\exp\left(\frac{-\pi fX}{V_S Q(f)}\right)\cdot G(f) \tag{3.1}$$

where $R_{\theta\varphi}$, ρ, V_s, X, $M_o(f)$, and $Q(f)$ are radiation pattern coefficient, density, S-wave velocity, distance, seismic moment and Q factor, respectively. If we assume a form for a regression analysis applied to ground motion data,

$$\log F(f) = a(f)M - (\log X + b(f)X) + c(f) \tag{3.2}$$

Comparing the two equations, regression coefficients, $a(f)$, $b(f)$, $c(f)$ are expressed in terms of physical parameters (e.g. Takemura et al., 1987).

$$M_0(f) = P_0(f)10^{a(f)M} \tag{3.3}$$
$$a(f) = (\log M_0(f) - \log P_0(f))/M \tag{3.4}$$
$$b(f) = (\log e)\pi f / V_S Q_S(f) \tag{3.5}$$
$$c(f) = \log\left(R_{\theta\varphi} P_0(f)\omega^2 G(f)/4\pi\rho V_S{}^3\right) \tag{3.6}$$
$$M_0(f) = 10^{a(f)M + c(f)} / \left(R_{\theta\varphi}\omega^2 / 4\pi\rho V_S{}^3\right) \tag{3.7}$$
$$Q_S(f) = (\log e)\pi f / V_S b(f) \tag{3.8}$$

These relations are valid not only for Fourier spectra but also for response spectra as indicated by Ikeura et al. (1991). In this study, we use acceleration response spectra with 5 percents damping *S(T)* in the form as shown in Equation (3.9),

$$\log S(T) = a(T)M - (\log X_{eq} + b(T)X_{eq}) + c(T) \tag{3.9}$$

where, T and X_{eq} are undamped proper period and equivalent fault distance defined by Ohno et al. (1998), respectively. Computations of equivalent source distances were conducted assuming the fault geometry determined by source inversions techniques referring the published data. We applied 1,988 horizontal motions from 18 earthquakes at hard rock sites of the KiK-net. We computed responses for 45 periods in the range between 1 to 10 sec..

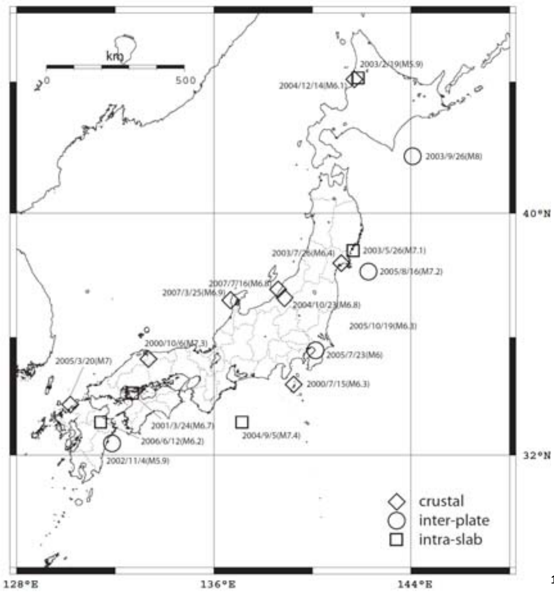

Figure 1 Location map of earthquake sources used in this analysis.

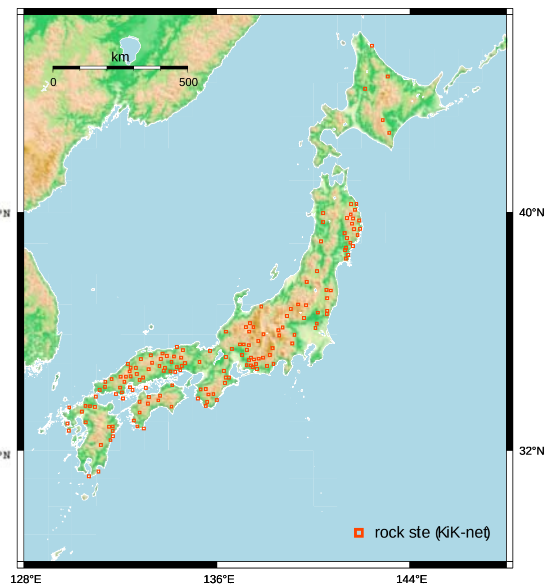

Figure 2 Location map of hard rock site used in this study

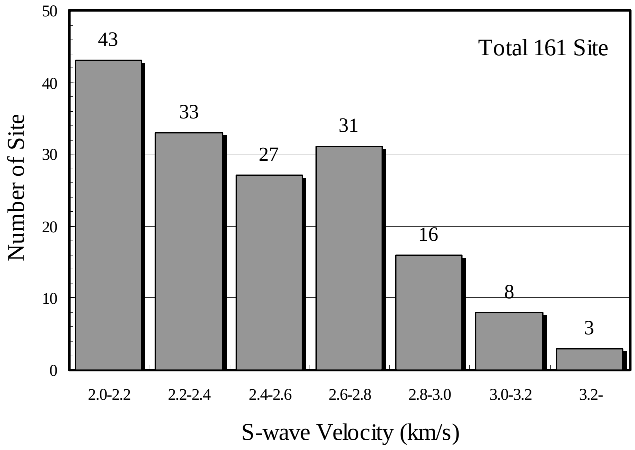

Figure 3 Histogram of S-wave velocity at hard rock KiK-net sites used in this study

4. RESULTS OF REGRESSION ANALYSIS

A two-step stratified regression analysis was applied to compute the coefficients *a*(*T*), *b*(*T*), and *c*(*T*). First, we obtained *b(T)* by assuming coefficients *a(T)* and *c(T)* to be a single variable. Next, we computed coefficients *a(t)* and *c(t)* using the determined coefficient *b(T)* by a first step. Thus obtained regression coefficients *a*(*T*), *b*(*T*), and *c*(*T*) are shown by solid (red) lines in Figure 4. The average standard deviation was 0.621 in terms of natural logarithms and it was relatively large compared with previous studies. This is the case that we used earthquake magnitudes M_{JMA} determined by JMA. We also obtained the coefficients by use of M_W (determined by F-net, Fukuyama et al., 1997) and compared with those of M_{JMA} as shown by broken lines in Figure 4. In addition to Figure 4, the regression coefficients proposed by Takahashi et al. (1998) are shown by dotted lines. The methods and the S-wave velocity of the sites by Takahashi et al. (1998) were quite similar to this study but their data were mostly from earthquakes of east coast and off south Tohoku to Kanto districts.

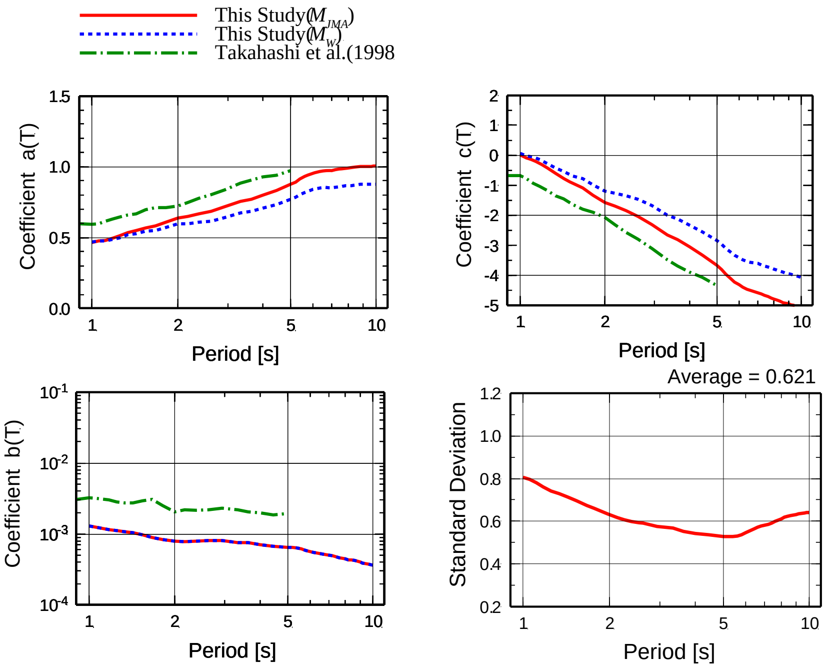

Figure 4 Results of regression analyses for M_{JMA} and M_W are compared with Takahashi et al. (1998).

The coefficients *b(T)* both of M_{JMA} and M_W are almost same, but the others differ systematically against period. This may due to that no significant difference between M_{JMA} and M_W are found for the inter-plate and intra-slab earthquakes, but M_{JMA} of inland crustal large earthquakes tends to exceed M_W. On the other hand, the absolute coefficients by Takahashi et al. (1998) are slightly biased with the present study, but the trends of coefficients against period are quite similar to those of present study.
Nevertheless those differences exist among three types of regression results, the differences of predicted *S*(*T*) based on the individual expressions were very small. Therefore, we use M_{JMA} hereafter for convenience of application in Japan.

5. SHAKEABILITY AT A SITE

We define "shakeability" simply by the ratio of the response spectrum at a site *j*, $S_j(T)$ to that of hard rock site, *S(T)* that is computed by equation (3.9),
In order to check validity of the proposed model, observed response spectra at the KiK-net sites of Hokkaido and Tohoku regions. Among them, three examples are shown in Figure 5. The averages of spectral ratios of observations to the standard model distribute mostly around unity and even in a worse case they are within a factor of two at longer period than 2 sec. We included data from smaller magnitude than 5.9 to obtain shakeability at a site, but to keep reliability at low frequency range, larger magnitude of 5.5 were finally used after consulting the quality of data.
We may say that the present model is valid for hard rock sites in average. However, an attention to large standard deviation should carefully be paid.

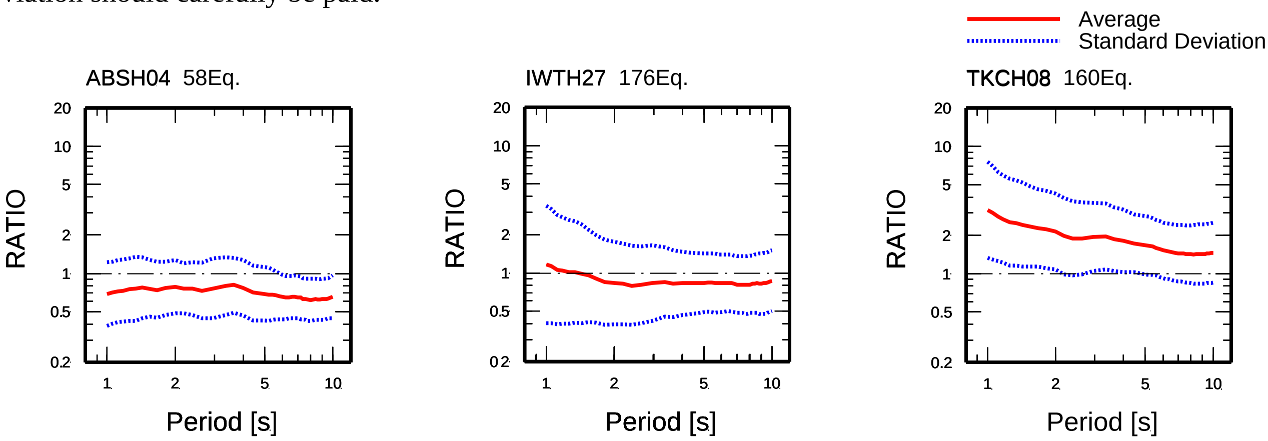

Figure 5 Shakeability(Average) and its standard deviation at hard rock sites

The targets are free surface motions obtained by the K-NET (Kinoshita, 1998) and the KiK-net to determine shakeability. As examples, we applied the same analysis to the data at HKD129 (Tomakomai, Hokkaido) and CHB009 (Chiba) that are located in large basins. They are shown in Figure 6, where thin (grey), thick (red) and broken lines represent the results of individual records, an average, and a standard deviation, respectively. The deviations are surprisingly large and the standard deviations of both sites are roughly factor of two. Therefore, it is very hard to apply in a straightforward manner using the average for assessing LGPM in engineering purposes.

6. DISCUSSIONS ON VALIDITY OF PREDICTIVE MODEL

During the 2003 Tokachi-oki earthquake (M_{JMA} 8.0), LPGM was severe in Yufutsu and Ishikari basins and damage to large oil tanks was observed (e.g. Hatayama et al. 2004, Koketsu et al., 2005). The distance from the hypocenter to the basins is roughly 200-260 km and K-NET and KiK-net sites locate in and around the basins as

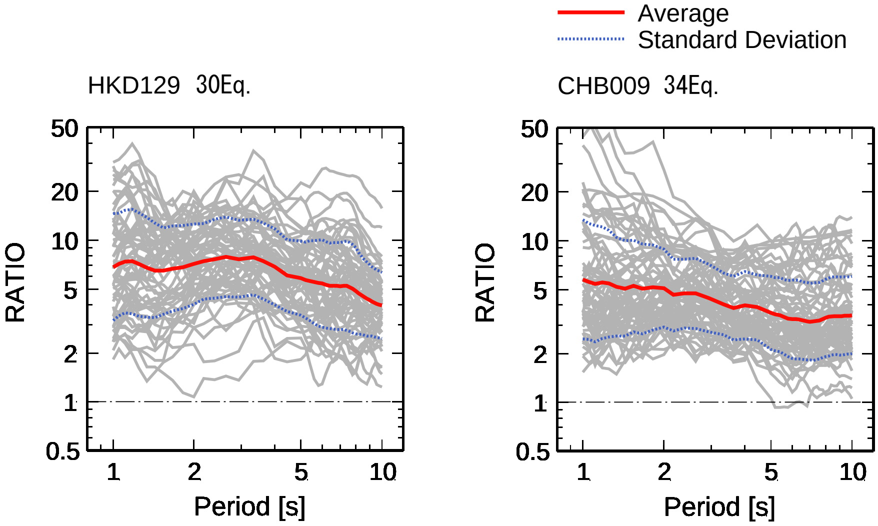

Figure 6 Shakeability (Average) and its standard deviation at thick sediment sites HKD129 and CHB009 that are located in large basins.

shown in Figure 7 by solid squares and open diamonds. Hatayama et al. (2004) obtained the spatial variation of LPGM, as a function of period, in terms of velocity response of 1 percent damping

The contours on the map shown in Figure 7(a) represent the observed velocity response at 7 sec. with 5 percent damping using the surface motion registered by KiK-net and K-NET from the 2003 Tokachi-oki earthquake. We examined to reproduce the observations using the standard attenuation model and the average sheakability, assuming the 2003 Tokachi-oki source model as shown in Figure 7(b). The pattern of contours is quite similar to the observation as shown in Figure 7(b), however; the reproduced absolute responses are systematically small compared with the observation.

When we use an average of the standard predictive model, source effects of radiation and directivity would be disappeared, so that it is plausible that predicted values do not necessarily match with the observations and underestimate at some directions. As a trial, we add one standard deviation for the standard predictive model to include those effects, irrespective to physical meanings. That is, the standard response spectrum on hard rocks is expressed as,

$$\log S(T) = a(T)M - \left(\log X_{eq} + b(T)X_{eq}\right) + c(T) + \sigma(T) \qquad (6.1)$$

where, $\sigma(T)$ represents one standard deviation shown in Figure . When we use the average shakeability at each site, a distribution of predicted velocity response comes to Figure 7(c). The pattern of shakeability is again quite similar to the observation, but the absolute values are still slightly less than the observation.

Next, we used the shakeability at each site by adding one standard deviation to the average and the result is shown in Figure 7(d). The last case well reproduces in terms of both space and shaking level, although the level is slightly large.

7. CONCLUSIONS

As a basic approach to understand long-period (1-10 sec.) ground motion (LPGM), we obtained an empirical standard spectral ground motion using the data of the KiK-net (NIED) on hard rock sites that the S-wave velocity of the site is higher than 2.0 km/s. The data from earthquakes of larger magnitudes than 5.9 were used. We applied the proposed empirical predictive model for estimating the shakeability at an arbitrary site using K-NET and KiK-net surface recordings. The LPGM has very strong spatial variation and a relative amplification at thick sediment sites are more than 10 times of rock sites and it also depends strongly on period. To examine the validity of our predictive model for LPGM, we compared the reproductions using our predictive model and the observations from the 2003 Tokachi-oki earthquake. A satisfactory result was obtained when we use the

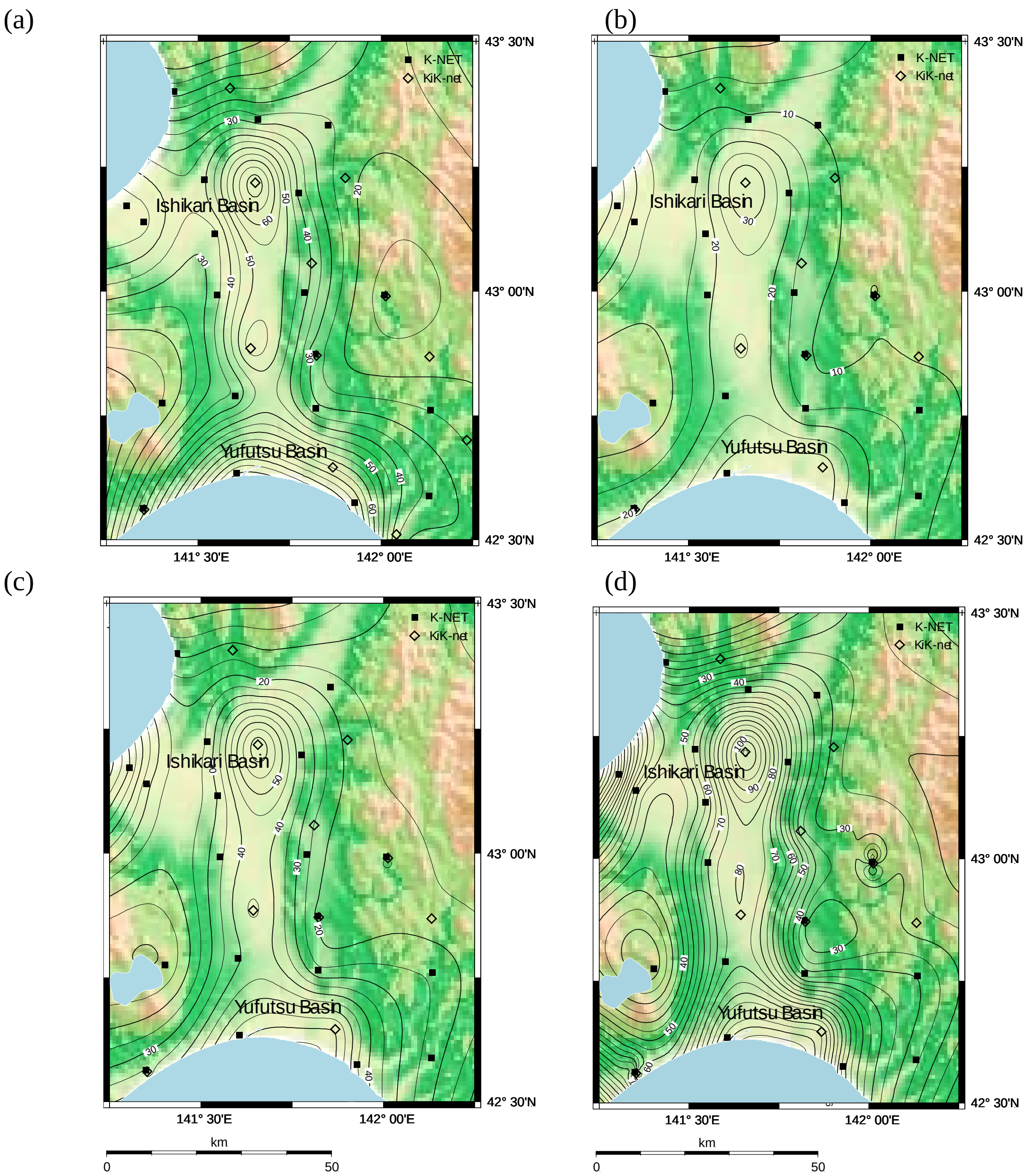

Figure 7 Contour maps of velocity responses with damping factor of 0.05 at a period of 7 sec in the Yufutsu and Ishikari-Basins. (a) **:**Observed velocity response from the 2003 Tokachi-oki earthquake; (b): reproduced using the averages of standard attenuation model and the average shakeability; (c):reproduced using the average plus one standard deviation as a standard rock motion, (d) reproduced using shakeability with the average and one standard deviation to the case shown in Figure 7(c).

standard LPGM attenuation model by adding one standard deviation to the average of hard rock motions and by adopting the shakeability by the sum of average and one standard deviation in terms of logarithmic scale.

The obtained shakeability may be useful for assessing seismic safety of long period structures. However, it is still uncertain whether the accounting one standard deviation for the predictive model of rock motion or for site amplification is satisfactory or not. Further study is certainly necessary. Present study modeled ground motion assuming body waves, but contribution of surface waves would much larger than body wave at longer distance from shallow earthquakes. How we include the effects of surface waves is our current and future target.

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