CHARACTERISTICS AND DISTRIBUTION OF STRONG GROUND MOTION DURING THE 2004 NIIGATA-KEN CHUETSU AND 2007 NIIGATA-KEN CHUETSU-OKI EARTHQUAKE IN JAPAN

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ABSTRACT :

Many houses and infrastructures were damaged during the 2004 Niigata-ken Chuetsu earthquake and the 2007 Niigata-ken Chuetsu-Oki earthquake in Japan. Distribution of peak ground motion is estimated in order to discuss the relation between the ground motion and damage grade. AVS30 in every 250x250m area is estimated by combining geomorphologic classification and borehole data. Distributions of seismic indices, peak ground velocity and JMA instrumental seismic intensity for the 2004 and 2007 earthquakes are estimated by the spatial interpolation based on Kriging method from the observed records. Non-linear amplification factor of surface soil is used in the estimation. The estimated distributions of strong ground motion are consistent with the damaged area and the liquefied area during the earthquakes.

KEYWORDS: AVS30, distribution of seismic indices, 2004 Niigata-ken Chuetsu earthquake, 2007 Niigata-ken Chuetsu-oki earthquake

1. INTRODUCTION

The 2004 Niigata-ken Chuetsu earthquake (Mj=6.8, Mw=6.6) occurred in the middle parts of Niigata prefecture in Japan. 68 persons were killed and more than 3,000 houses were severely damaged during the earthquake. Severe damage occurred in Odiya city, Yamakoshi village and Kawaguchi village where are located just over the source thrust fault. Three years later, the 2007 Niigata-ken Chuetsu-oki earthquake (Mj=6.8, Mw=6.6) occurred in offshore region of the same prefecture. 15 persons were killed and more than 1,000 houses were severely damaged. Severe damage occurred in Kashiwazaki city and Kariwa village where are located beside the source fault parallel to the coastline. The distance between the epicenters of the 2004 and 2007 events is about 50 km. The severe damaged areas do not overlap, whereas some infrastructures such as railways, highways and lifelines were temporally stopped after both earthquakes.

Many strong ground motion records were observed by a number of organizations. During 2004 Chuetsu earthquake, ground motions with 1.3 sec of predominant period are observed in Kawaguchi village where severe damage occurred. During 2007 Chuetsu-oki earthquake, ground motions with 2.2 sec of predominant period are recorded in Kashiwazaki city. Longer predominant period of about 3 sec is observed in Kariwa village. Characteristics of damages around the observation sites can be discussed from the records, whereas it is difficult to discuss the distribution of the strong ground motion based on the observed records.

Estimation of amplification in surface soil is very important in order to estimate detail distribution of ground motion. AVS30 (average shear wave velocity to 30 m depth) in every 250x250m area is estimated by a proposed method, which combines geomorphologic classification and borehole data. We collected about 3000 borehole data including N-values. The distributions of ground motion during both the 2004 and 2007 earthquakes are estimated by the spatial interpolation using Kriging method based on the observed records.

2. METHOD

2.1. Nonlinear Amplification Model of Surface Soil

Damages of urban structures are estimated by some seismic indices of strong ground motion such as PGA and PGV because the indices are easy to be obtained immediately after the earthquake in order to grasp a distribution and a level of the damages. For this objective, a dynamic response of a surface soil is approximated by an simple amplification factor λ (Suetomi and Yoshida, 1998);

$$X_S = \lambda(X_b) \cdot X_b \tag{2.1}$$

where X_S denotes the index on the ground surface, X_b the index on outcrop of the engineering seismic base layer. The amplification factor λ should be a function including the argument X_b because the surface soil shows nonlinear behavior depending on the magnitude of input ground motions. The function λ should be modeled by a monotone decreasing function in Eqn. 2.1.

However, a change of the amplification factor should be small when a shear strain in the surface soil is smaller than about 10^{-5}, which is the shear strain corresponding to a small change of rigidity and damping ratio. The amplification factor should be constant for the small input ground motion. In addition, the peak ground motion has an upper limit because the surface soil cannot transfer a shear stress larger than its shear strength. Suetomi *et al.* (2004, 2006) proposed another model described by Eqn. 2.2 which consists of three domains as shown in Figure 1.

$$\begin{aligned} &X_S = \alpha \cdot X_b \quad (X_b \le X_1) \\ &X_S = X_L - \beta \cdot (X_b - X_2)^2 \quad (X_1 < X_b < X_2) \\ &\qquad X_2 = \frac{2}{\alpha} X_L - X_1, \qquad \beta = \frac{X_L - \alpha \cdot X_1}{(X_2 - X_1)^2} \\ &X_S = X_L \quad (X_b \ge X_2) \end{aligned} \tag{2.2}$$

In the first domain, λ is constant because the input motion is small. In the second domain, the function smoothly connects the first and third domains. In the third domain, the amplification factor satisfies that the indices on the ground are equal to the upper limit X_L. Parameters in Eqn. 2.2 for PGA and SI are functions of average S-wave velocity in the top 20 m soil (denoted by AVS20) as follows.

$$\log(\alpha_{PGA}) = 2.024 - 0.75 \log_{10}(AVS20) \tag{2.3}$$

$$\log(PGA_1) = 1.4 \log_{10}(AVS20) - 0.8 \tag{2.4}$$

$$\log(PGA_L) = 1.0 \log_{10}(AVS20) + 0.778 \tag{2.5}$$

$$\log(\alpha_{SI}) = 1.889 - 0.7 \log_{10}(AVS20) \tag{2.6}$$

$$\log(SI_1) = 1.6 \log_{10}(AVS20) \tag{2.7}$$

$$\log(SI_L) = 0.8 \log_{10}(AVS20) + 0.48 \tag{2.8}$$

The amplification factor α for weak motion is estimated using the relation by Tamura *et al.* (2000). 500 m/s of AVS20 is regarded as a base layer (α=1.0). For PGV, λ is constant because a nonlinear behavior of the surface soil little affects the amplification factor.

The relation of JMA instrumental Seismic Intensity (IJ) between the ground surface IJ_s and the seismic base layer IJ_b is represented as $IJ_s = IJ_b + \lambda_{IJ}$, where the amplification factor λ_{IJ} is expressed as follows;

$$
\begin{aligned}
\lambda_{IJ} &= \alpha_{IJ} && (IJ_b \le IJ_1) \\
\lambda_{IJ} &= \alpha_{IJ} - \beta_{IJ}(IJ_b - IJ_1) && (IJ_1 < IJ_b \le IJ_2) \\
\beta_{IJ} &= \frac{\alpha_{IJ} - IJ_L + IJ_2}{IJ_2 - IJ_1} && \\
\lambda_{IJ} &= IJ_L - IJ_b && (IJ_2 \le IJ_b)
\end{aligned}
\tag{2.9}
$$

The parameters in Eqn. 2.9 are functions of AVS20 as follows;

$$\alpha_{IJ} = 2.699 - \log_{10}(AVS20) \tag{2.10}$$
$$IJ_1 = 0.8 + 2.25\log_{10}(AVS20) \tag{2.11}$$
$$IJ_2 = 1.15 + 2.4\log_{10}(AVS20) \tag{2.12}$$
$$IJ_L = 2.2 + 2.0\log_{10}(AVS20) \tag{2.13}$$

Amplification characteristics of the proposed relationship depending on AVS20 are shown in Figure 2. The indices on the ground surface for soft soil are larger than those for stiff soil when the input motions are weak. However, the indices for soft soil are not always the most amplified ones when the input motions are strong. The nonlinear effect explains well observed relations during the 1995 Hyogoken-Nambu (Kobe) earthquake.

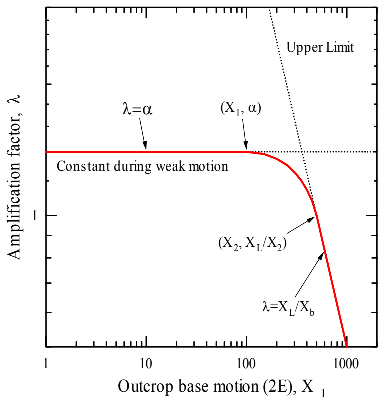
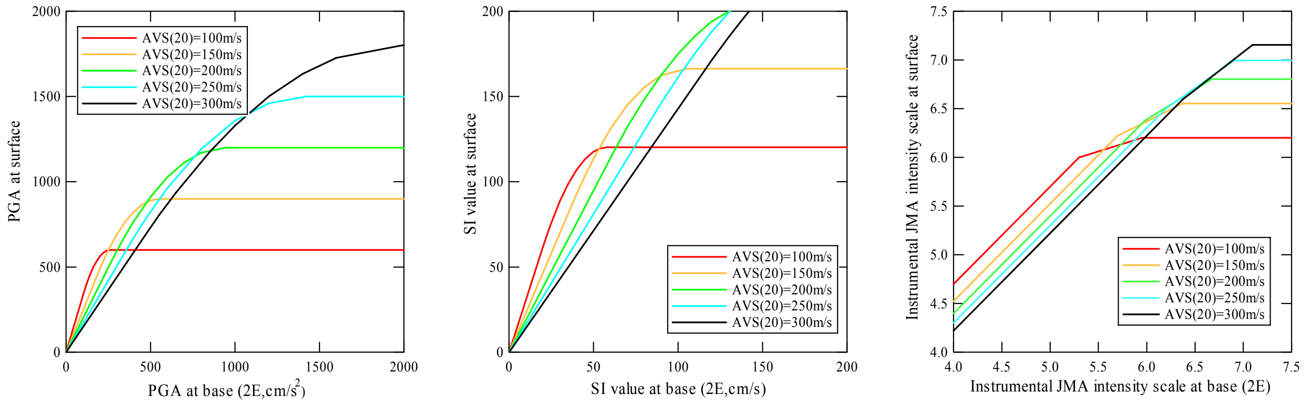


Figure 1: Nonlinear amplification model



(a) PGA (b) SI value (c) JMA instrumental seismic intensity

Figure 2: Amplification characteristics depending on average shear wave velocity

2.2. Estimation of AVS30 Map

In order to estimate a distribution of the indices, we need AVS30 map in the Chuetsu area. AVS20, which is used to estimate a non-linear amplification factor described above, is assumed equal to AVS30 in this study. We collect borehole data in the Chuetsu area from many organizations in order to evaluate the spatial distribution of AVS30. Since we can have a small mount of shear wave velocity (*Vs*) values directly measured in the situation, the following empirical formulas are used to estimate *Vs* from SPT-N values (Japan Road Association, 1996);

$$\text{for sandy soils: } V_S = 80N^{1/3} \text{ (cm/s)} \tag{2.14}$$

$$\text{for clay soils: } V_S = 100N^{1/3} \text{ (cm/s)} \tag{2.15}$$

In the plain of Nagaoka city, where we have dense borehole data, AVS30 values can be estimated by a simple interpolation method. In mountainous area, however, the data is not enough to apply the simple interpolation.

A digital map of ground conditions in every 1x1 km size of mesh, named "Japan Engineering Geomorphologic Classification Map" (Wakamatsu *et al.*, 2005), covered the entire region in Japan. Wakamatsu and Matsuoka (2005) developed higher resolution (250x250 m) map of the geomorphologic classification in Niigata prefecture including the Chuetsu area. Matsuoka *et al.* (2006) proposed a method to evaluate AVS30 for each geomorphologic class depending on altitudes (E_v), slope gradients (S_p) and distances from mountains (D_m) as follows;

$$\log AVS30 = a + b\log Ev + c\log Sp + d\log Dm \tag{2.16}$$

In this study, we average AVS30 estimated by the borehole data and AVS30$_g$ by the geomorphologic classification using weights of the distance from the borehole sites. The following equation represents the averaged AVS30 as

$$\overline{AVS30_j} = \frac{\sum_{i=1}^{n} w_{ij} AVS30_i + w_g AVS30_g}{\sum_{i=1}^{n} w_{ij} + w_g} \tag{2.17}$$

$$w_{ij} = \frac{\xi}{r_{ij}^m},\ w_g = \frac{1}{r_g^m} \tag{2.18}$$

where r_{ij} is the distance between the center of j-th mesh and i-th borehole site. The coefficient ξ is used to consider the weight of the borehole data to the geomorphologic classification. ξ=10, r_g=1km, m=2 are adopted in the following calculations.

2.3. Estimation of Seismic Indices

The mean value of PGV on the seismic base layer is represented by Eqn. 2.19 proposed by Si and Midorikawa (1999).

$$\log_{10} PGV = 0.58M_w + 0.0038h - 1.29 - \log_{10}(r + 0.0028 \cdot 10^{0.5M_w}) - 0.002r \tag{2.19}$$

where r is a fault distance, M_W the moment magnitude, h the hypocentral depth. The PGV obtained by Eqn. 2.19 may be different from the observed value during each earthquake because it is a mean value. A simple Kriging method with a trend component, which is represented by the attenuation curve Eqn. 2.19, is applied to the spatial interpolation. Residual errors are assumed to be a normal stochastic field whose mean value is zero and covariance is exponential function. The correlation distance is set to be 20 km.

Trend component of JMA instrumental Seismic Intensity on the base layer is calculated from the mean PGV by Eqn. 2.19 as follows;

$$IJ = 2.30 + 2.01 \cdot \log_{10} PGV \tag{2.20}$$

The simple Kriging method is also applied to estimate the distribution of indices.

The amplifications factors are evaluated from the indices in the base layer. The amplification factor of PGV estimated by Midorikawa *et al.*(1994) is applied. Eqn. 2.2 and Eqn. 2.9 are applied for the factors of the other indices.

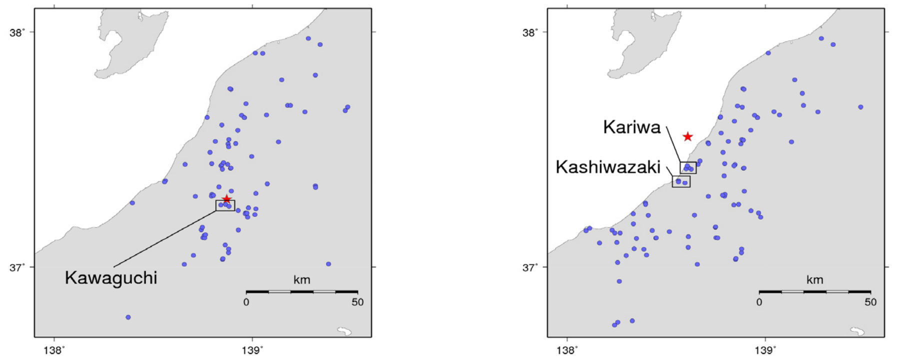
3. OBSERVED RECORDS OF STRONG GROUND MOTION

Figure 3 shows the site locations of ground motion records used in order to estimate the distribution of seismic indices. 78 sites are adopted for the 2004 Chuetsu earthquake, which are operated by Japan Meteorological Agency (JMA) (8 sites), Niigata prefecture (22 sites), National Research Institute for Earth Science and Disaster Prevention (NIED) (18 sites from K-NET, 8 sites from KiK-net), Ministry of Land, Infrastructure, Transport and Tourism (MLIT) (6 sites), Japan Highway Public Corporation (JH) (7 sites), East Japan Railway Company (JR-EAST) (8 sites) and the other organization (1 site). 95 sites are also used for the 2007 Chuetsu-oki earthquake, by JMA (7 sites), Niigata prefecture (41 sites), Nagano prefecture (4 sites), NIED (19 sites from K-NET, 8 sites from KiK-net), East Nippon Expressway Company (E-NEXCO) (12 sites), Tokyo Electric Power Company (TEPCO) (3 sites) and Gas and Water department of Kashiwazaki city (1 site). We briefly introduce the characteristics of several records in the severe damaged area in the following paragraphs.

During 2004 Chuetsu earthquake, dense distribution of ground motion records is obtained around the epicenter. 3 sites are located in Kawaguchi village, major damaged area shown in Figure 3(a). The sites are operated by Niigata prefecture (LGV KWG), JR-EAST (JR Skw) and JH (JH Ekw). Figure 4 shows velocity waveforms of the EW components. Peak velocities of these components exceed 100 cm/s. Figure 4 also shows the pseudo velocity response spectra (h=0.05) of these components. About 500 cm/s of peak values at 1.3 sec of peak period are clearly obtained for LGV KWG and JR Skw, which are similar to that of JR Takatori wave observed during 1995 Hyogoken-Nambu (Kobe) earthquake in the severe damaged area.

During 2007 Chuetsu-oki earthquake, dense distribution of ground motion records is also obtained. 4 sites are located in the downtown of Kashiwazaki city shown in Figure 3(b). The sites are operated by NIED (K-NET NIG018), Niigata prefecture (LGV KSCH), Gas and Water department of Kashiwazaki city (Gas KGM) and JR-EAST (JR Kzk). Figure 5 shows acceleration waveforms of the normal components (N125E) of the seismic fault. Three predominant phases are clearly observed. The sharp peaks after the second phase may be generated by the cyclic mobility due to liquefaction (Yoshida *et al.*, 2007). Figure 5 also shows the pseudo velocity response spectra (h=0.05) of these component. About 500 cm/s of peak values at 2.2 sec of peak period are clearly obtained.

The other 4 sites are located in Kariwa village and its vicinity shown in Figure 3 (b). The sites are operated by TEPCO (TEPCO KKZ5G1, TEPCO KKZ1G1 and TEPCO KSHSG1) and Niigata prefecture (LGV KRWM). Figure 6 shows velocity waveforms of N125E component and its pseudo velocity response spectra (h=0.05). The spectral response values of TEPCO KSHSG1 and LGV KRWM are small in short period and large in long period in comparison with the other 2 sites. It should be noted that about 600 cm/s of peak value at about 3 sec of peak period is observed at LGV KRWM. This record is quite important to consider a seismic design for long period structures.



(a) the 2004 Chuetsu earthquake (78 sites) (b) the 2007 Chuetsu-oki earthquake (95 sites)

Figure 3: Observation sites in order to estimate the distribution of the seismic indices

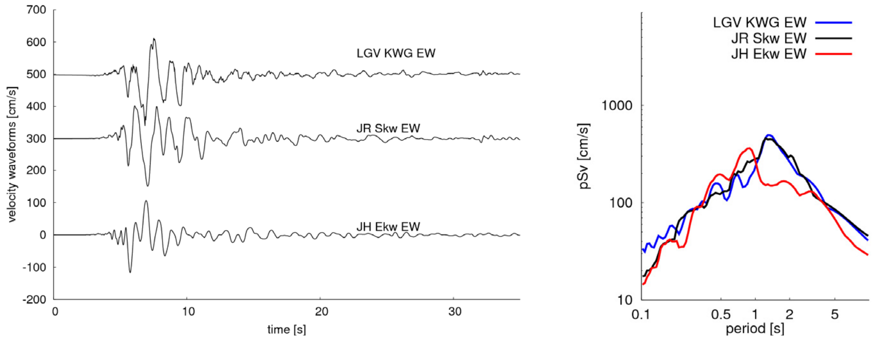


Figure 4: Velocity waveforms (left) and pseudo velocity response spectrum (right) in Kawaguchi village

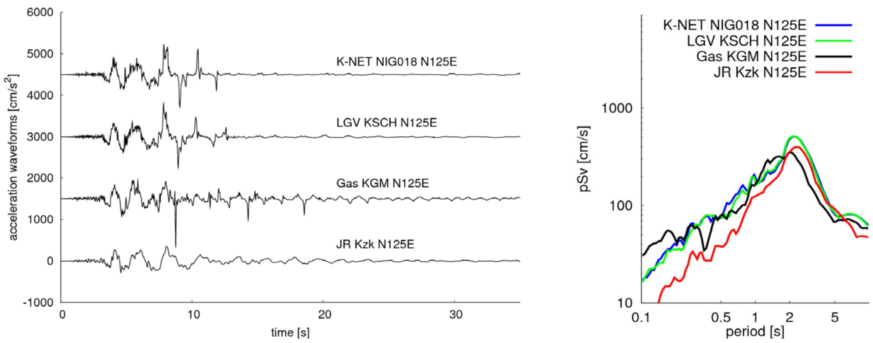


Figure 5: Acceleration waveforms (left) and pseudo velocity response spectrum (right)
in the downtown of Kashiwazaki city

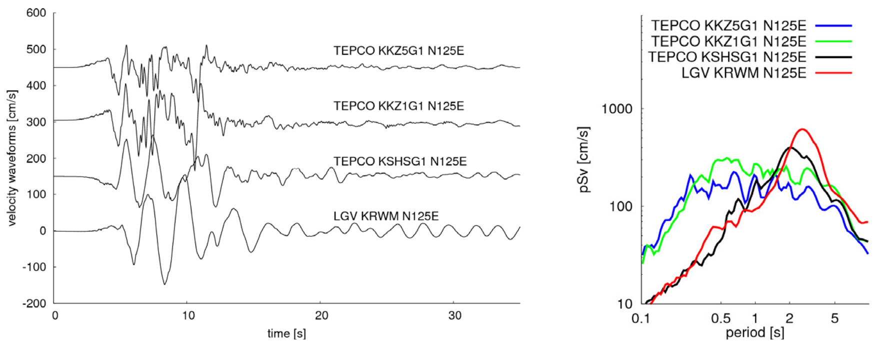


Figure 6: Velocity waveforms (left) and pseudo velocity response spectrum (right)
in/around Kariwa village

4. DETAILED DISTRIBUTION OF PEAK GROUND MOTION

Figure 7 shows the distributions of PGV and SI during the 2004 Chuetsu earthquake considering nonlinear effect of surface soil using the amplification function shown in Figure 2. The results indicate that the strong ground motion is estimated over the fault plane and along the Shinano river, where the many damages of houses and landslides were observed.

Figure 8 shows the distribution of SI during the 2007 Chuetsu-oki earthquake. The strong ground motions are estimated along the coast line. For detail discussion of the distribution, AVS30 is interpolated into 50x50 m areas. Figure 9 shows the close-up distributions of PGA and SI in the plain area whose height is lower than 50 m. The region also overlaps with the damaged area and the liquefied area. Large PGV is estimated in Kariwa village and its vicinity where a backmarsh of the hill parallel to the coastline is located. The reason may be quantitatively evaluated by considering the source, deep subsurface structure and soft surface layer effects.

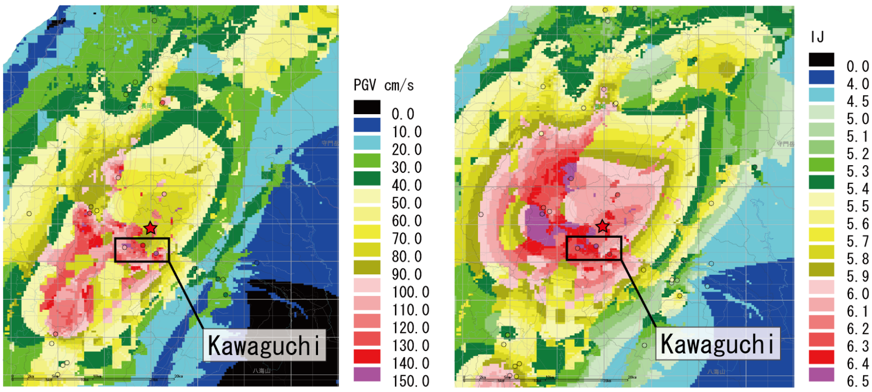


Figure 7: Estimated distribution of seismic indices during 2004 Chuetsu earthquake
(PGV: left, JMA instrumental seismic intensity: right)

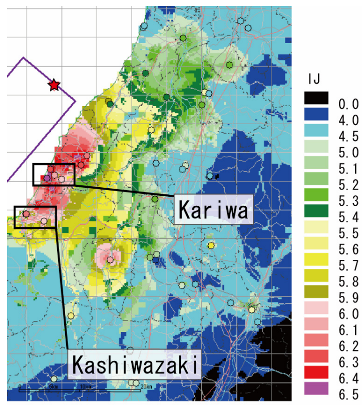
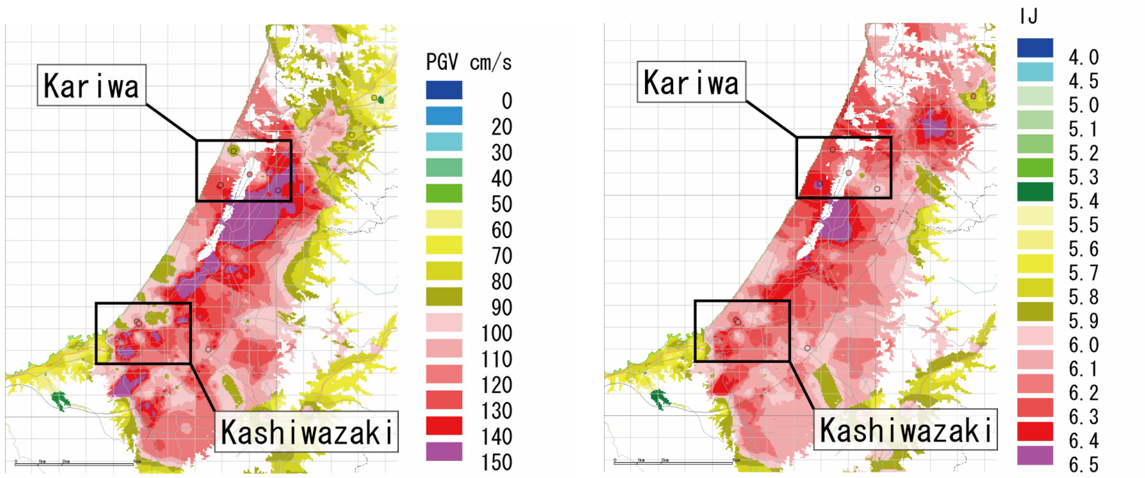


Figure 8: Estimated distribution of JMA instrumental seismic intensity during 2007 Chuetsu-oki earthquake



(a) PGV (b) JMA instrumental seismic intensity

Figure 9: Estimated distribution of seismic indices during 2007 Chuetsu-oki earthquake (50x50 m area)
(PGV: left, JMA instrumental seismic intensity: right)

5. CONCLUSION

AVS30 in every 250x250m area is estimated by combining geomorphologic classification and borehole data in the Chuetsu area of Niigata prefecture, Japan. The distributions of seismic indices, peak ground velocity and JMA instrumental seismic intensity, during the 2004 Niigata-ken Chuetsu and the 2007 Niigata-ken Chuetsu-oki earthquakes are estimated by the spatial interpolation based on Kriging method from the observed records. Non-linear amplification factor of surface soil is used in the estimation. The strong ground motion during the 2004 earthquake is estimated on the soft soil along the Shinano river, while that during the 2007 earthquake is distributed on the backmarsh behind the hill parallel to coastline. Both the regions are consistent with the damaged area and the liquefied area.

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