Ground Motion Estimation in the Near-source Region during the 2007 Niigata-ken Chuetsu-oki Earthquake

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ABSTRACT :

We performed a damage survey of temples and shrines near the source region of the 2007 Niigata-ken Chuetsu-oki earthquake to estimate the distribution of strong ground motions. We constructed a function to estimate PGV (peak ground velocity) from the damage rank of main hall of temples and shrines, and estimated the PGV distribution in the source region. From our results, the PGV in the most of the Kashiwazaki basin exceeds 100cm/s. This PGV distribution agrees with the PGV estimated from the attenuation relationship and surface soil amplification. The conventional estimation method using the ratio of overturned tombstones underestimates the PGV in the basin.

KEYWORDS: Peak Ground Velocity, Source Region, Ratio of Overturned Tombstones, Structure of temples and shrines, 2007 Niigata-ken Chuetsu-oki Earthquake

1. INTRODUCTION

The 2007 Niigata-ken Chuetsu-oki earthquake (M_w 6.6, M_{jma} 6.8)[1] produced severe damage in buildings, civil structures, soil deformation in the near-source region. The Kashiwazaki-Kariwa Nuclear Power Plant, which is located at 15km south of the epicenter, was subjected to strong shaking, and the strong motion record observed at the reactor was greater than the design load.

Five strong motion records of the 2007 Niigata-ken Chuetsu-oki earthquake were recorded within 10 kilometers from the source fault; 4 strong motion stations and the nuclear power plant site[2] (Figure 1). The observed PGV (peak ground velocity) varies from 50 to 100 cm/s (Table 1), which shows the inhomogeneous velocity distribution around the near-source region. Moreover, the predominant period of the waveforms has large variety depending on the location of the stations. For example, the waveform in the downtown Kashiwazaki shows very long period (longer than 2 seconds) ground motion and strong nonlinearity of the soil. The sedimentary soil structure in this region was very complicated[3] and it greatly affects to the ground motion amplification.

Our group performed a damage survey of temples and shrines near the source region of the 2007 Niigata-ken Chuetsu-oki earthquake from 25th to 27th of July, 2007 and surveyed the damage rank of the structure and ratio of overturned tombstones. It is conventional to estimate the ground motion from the ratio of overturned tombstones and damage rank of the structure, and various methods are proposed in the past research[4-5]. Although there are many difficult problems in estimating ground motions in this region due to the complicated sedimentary structure and soil non-linearization, we tried to evaluate how much ground motion we can estimate from the survey results based on the empirical relationship between the ground motion and damage. This paper focuses on the following topics:

- Construct an empirical function to estimate peak ground velocity from the damage rank of main hall of temples and shrines, and characterize the average PGV distribution in the near-source region.

- Apply the conventional relationship of the ratio of overturned tombstones to the survey results, compare with the observed PGV, and evaluate the applicability of the conventional relationship to this earthquake.
- Estimate the near-source PGV from the attenuation relationship and compare with the PGV distribution computed from the survey results.

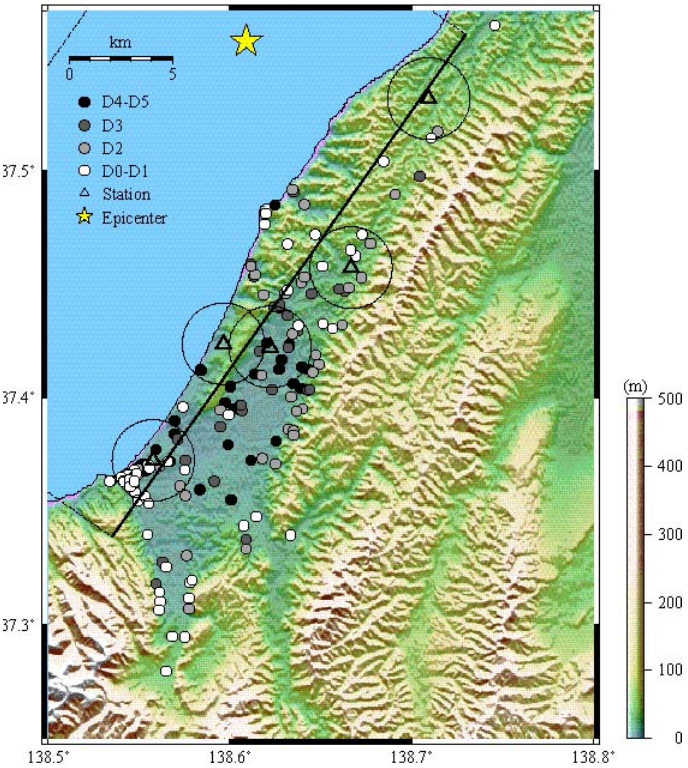

Figure 1 Observation sites and geography of the near-source region.

(a) damage rank D3

(b) damage rank D4

Figure 2 Examples of the damage rank of a main hall of temples and shrines.

2. SURVEY METHOD

We performed a damage survey of temples and shrines in the east side of the near-source region. The survey area covers from Izumozaki to Kashiwa, 30km*20km wide in the north-south and east-west direction, respectively (Figure 1). The total number of the sites we surveyed was 212 shrines, temples and graveyards. More detail number is; 74 temples and shrines with graveyards, 81 temples and shrines without graveyards, and 57 sites with only graveyards. A group of two or three people surveyed each site and recorded the damage condition. The latitude and longitude of the sites were measured by a handy GPS.

Damage rank (DR) of the structures such as main halls and belfry (a building in which a bell is hung) was categorized in D0 (no damage), D1-D2 (little damaged), D3 (severely damaged; see Figure 2), D4-D5 (totally collapsed; see Figure 2) based on the Wooden structure damage pattern by Okada and Takai[6]. Internal damage which cannot be recognized from the outside was not evaluated. In graveyards, the tombstones with about 80cm height were selected and the ratio of the overturned tombstones against the total number of tombstones was counted. In some graveyards, 2-3 tombstones were selected arbitrarily and measured the length, width and breadth. Graveyards with tombstones less than 10 and with tombstones repaired after the earthquake were removed from the data analysis. We also recorded the damage rank of objects such as shrine gates and statues.

3. RELATIONSHIP BETWEEN OBSERVED RECORDS AND DAMAGE RANK

3.1. Frequency Characteristics of the Observed Seismograms

In order to characterize the relationship between PGV and damage rank of main hall of temples and shrines, the damage rank is calibrated by the observed record in the near-source region. The observed records used for the calibration are 5 stations; JMA Izumozaki (Izumozaki), Nishiyama-branch of Kashiwazaki city hall (Nishiyama), Kariwa town house (Kariwa), K-NET Kashiwazaki (NIG018, in the Kariwa city hall), service hall of the Kashiwazaki-Kariwa nuclear power plant (KKNPP). The frequency characteristics of each record are shown in Table 1. The records observed at the 1st and 5th reactors of the KKNPP are also included in the Table 1. These stations are removed from our analysis since we do not have an access to these sites to perform damage survey in the surrounding area.

Since each record was recorded by the accelerometer, the DC offset of the accelerograms was corrected by subtracting the mean of the pre-event portion. The baseline correction scheme[7] was applied and we obtained appropriate velocity records by the single integration. The larger maximum amplitude of horizontal NS and EW components is used as the PGV. The same component as PGV is selected for the values of PGA. The predominant period of the ground motion is computed by the following equation:

$$T_e = 2\pi / (PGA / PGV) \tag{1}$$

ARV will be explained in the section 4.1. The ambient noise was measured at four sites except the KKNPP, and the predominant frequency of the H/V spectrum from the ambient noise measurement is also shown in the Table. The predominant frequency of the Kariwa and K-NET Kashiwazaki was as long as 1.25 seconds, and it is clearly different from that of Nishiyama. There is no clear peak in the spectrum of the Izumozaki record.

Figure 3 shows the horizontal acceleration response spectrum of each record. The records of the Izumozaki and Nishiyama shows clear peak at around 0.5 second and quickly falls down in longer period component. On the other hand, the three records in Kashiwazaki basin (Kariwa, K-NET Kashiwazaki, KKNPP) show the large response from 1 to 3 seconds.

3.2. The relationship between observed records and damage rank of main hall of temples and shrines

In this section, the relationship between observed records and damage rank of main hall of temples and shrines around the seismic stations is analyzed. We defined the circle with the constant radius from the station as the station neighborhood. The size of the radius is 2km. This size is determined so that we have enough samples in the circle, as well as it is sensitive enough to characterize the geographical and topographical changes. The station neighborhood is shown in Figure 1 as an open circle. At least 9 survey sites are included in the station neighborhood except Izumozaki and KKNPP. Although the number of the survey sites near Izumozaki is only two, the result (D2:1 structure, D0-D1:1 structure) agrees with the damage condition in that region. As for KKNPP, most of the neighborhood is covered by the nuclear power plant site, so we cannot access the area.

Figure 4 shows the relationship between observed PGV (PGV_{obs}) and the D3 and D4 damage ratio of the main hall of temples and shrines. Here, D3 (D4) damage ratio means the ratio of the damaged buildings subjected to the damage of greater equal to D3 (D4) level against the total buildings. D3 and D4 damage ratio tends to increase as the PGV increases. This relationship is regressed by the cumulative probability density function of the lognormal distribution $\Phi(x)$ and a PGV_{obs} - damage ratio function is obtained. The probability (P_{DR}) that the main hall is subjected to the damage greater than DR at some PGV is expressed by using the average λ and the standard deviation ζ of ln(PGV);

$$P_{DR}(PGV) = \Phi((\ln(PGV)-\lambda)/\zeta) \tag{2}$$

λ and ζ are determined by the least square method with probability paper. The obtained regression coefficients are;

D3 damage ratio: $\lambda = 4.61, \zeta = 0.31$
D4 damage ratio: $\lambda = 4.81, \zeta = 0.19$

These regression curves are added in Figure 4.

Table 1 List of the strong motion records.

No.	Station name	Latitude	Longitude	Intensity	PGA (cm/s^2)	PGV (cm/s)	T_e (s)	ARV	T(s) from ambient noise
1	Izumozaki	37.532	138.710	5.9	494	48	0.61	1.19	unclear
2	Nishiyama	37.457	138.667	6.2	841	78	0.58	1.56	0.31
3	Kariwa	37.422	138.622	6.0	465	121	1.63	2.35	1.25
4	KKNPP	37.424	138.597	6.1	437	130	1.87	2.09	–
5	K-NETKashiwazaki	37.372	138.558	6.4	668	110	1.03	2.09	1.25
6	1st reactor of KKNPP	37.424	138.597	6.5	890	167	1.18	2.09	–
7	5th reactor of KKNPP	37.436	138.602	6.4	1223	90	0.46	2.09	–

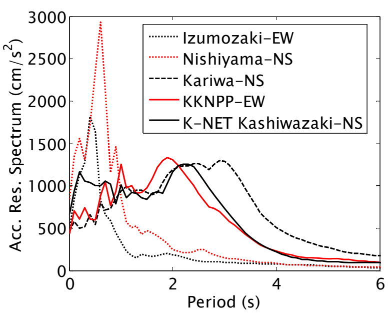

Figure 3 Response spectrum of acceleration.

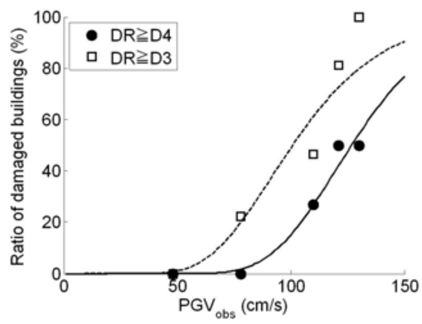

Figure 4 PGV_{obs} and DR of main halls.

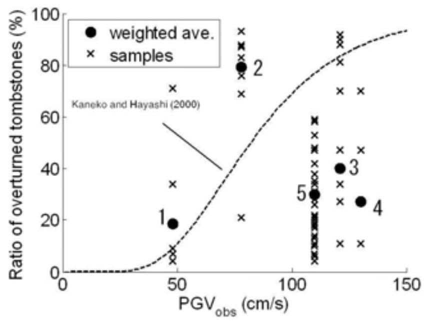

Figure 5 PGV_{obs} and ratio of the oberturned tombstones.

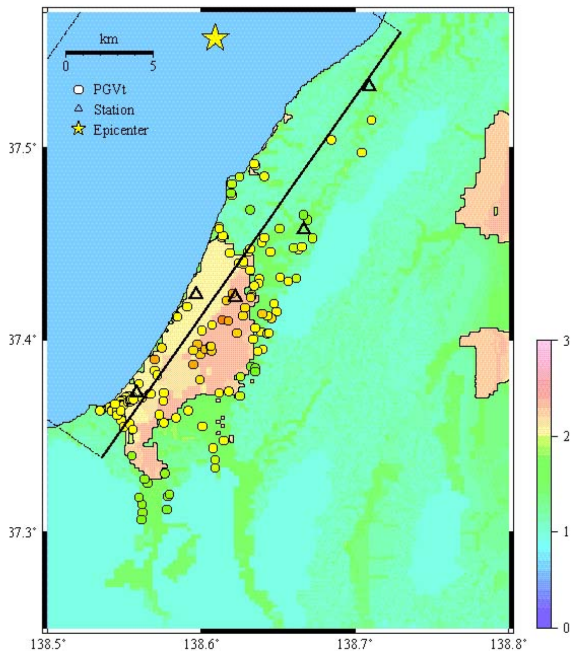

Figure 6 PGV estimated DR of main halls and ARV distribution.

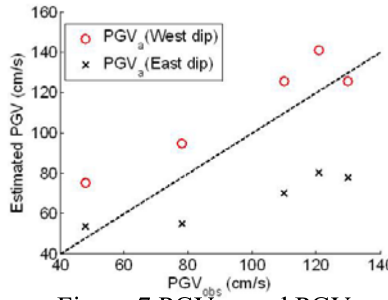

Figure 7 PGV_{obs} and PGV_a.

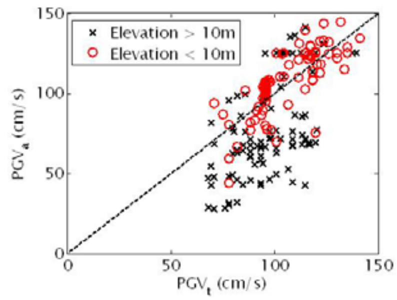

Figure 8 PGV_t and PGV_a.

3.3. The relationship between the observed records and ratio of overturned tombstones

Figure 5 shows the relationship between the observed PGV (PGV_{obs}) and ratio of overturned tombstones. The "x" symbol is the ratio of overturned tombstones of each site, and solid "o" symbol is the average weighted by the number of the tombstones of each site. The broken line represents the empirical function ($\lambda=4.41$, $\zeta=0.4$) proposed by Kaneko and Hayashi[5]. In general, the ratio of overturned tombstones has a good correlation with PGV. However, this figure does not show the positive correlation.

According to Kaneko and Hayashi[5], the ratio of overturned tombstones shows a good correlation with PGV if the equivalent natural period of the tombstone (T_b) is greater than the predominant period of the ground motion (T_e). The equivalent natural period of the tombstone (T_b) is defined by the following equation:

$$T_b = H^{0.5}(1 + B/H)^{1.5}/15.6 \qquad (3)$$

where H is the height (cm) and B is width (cm) of the tombstone. We selected samples of the tombstones randomly and measured B and H. The average H is 76cm, B/H is 0.40, and T_b computed from the average aspect ratio is 0.93 second. The station with predominant period of the PGV_{obs} less than 0.93 was only Izumozaki and Nishiyama (see Table 1), so the empirical function by Kaneko and Hayashi[5] cannot be applied to some regions.

Figure 5 shows the PGV estimated from the ratio of overturned tombstones underestimates observed PGV in the neighborhood of the station with T_e greater than 0.93 second. However, the Nishiyama whose T_e was shorter than 0.93 second does not fit the empirical function by Kaneko and Hayashi either, which means the empirical function cannot be applied in this region. Although the empirical function of the ratio of overturned tombstone for the ground motion with predominant period longer than 1 second was analytically shown in Kaneko and Hayashi (2000), it has not been observed in the past earthquake damage. Figure 5 shows the limitation of the empirical function of the ratio of overturned tombstone to the long period ground motion in the real data.

4. GROUND MOTION ESTIMATION IN THE NEAR-SOURCE REGION

4.1.PGV Estimation from the Attenuation Relationship and ARV

In order to check the accuracy of the PGV estimation, the estimated PGV is compared with the PGV computed from a different method. We use the attenuation relationship of PGV[8] and velocity amplification factor (ARV) computed from the average S-wave velocity in the upper 30m of the ground (AVS30). We follow the methodology used by Fujiwara et al.[9]. The PGV estimated by this method is called as PGV_a.

The fault section to compute the fault distance (a minimum distance between station and fault) is 3D west-dip model used for the waveform inversion by Aoi et al.[10] Since the attenuation relationship cannot be applied to the region very close to the fault, the minimum fault distance is set to be 3km. In order to compute the ARV, The 250m mesh geography data in Niigata[11] and 50m mesh topographical data[12] were used based on the method proposed by Matsuoka et al.[13]

Figure 6 shows the ARV distribution in the near-source region. The black rectangle is fault surface by Aoi et al., [11] and the black curve is a contour of ARV 2.0. The high ARV region surrounded by the contour is classified as a back marsh, sand dune, delta, or coastal lowland, which cover most of the Kashiwazaki basin.

Figure 7 shows the relationship between PGV_{obs} and computed PGV_a. PGV_a of most of the stations agrees with the observations except Izumozaki. There is a possibility that the slip on the fault around Izumozaki was small, and that produced the smaller ground motion. Since the method used by Fujiwara et al. considers only the fault distance and surface soil amplification, the estimated PGV distribution may not be true depending on the slip distribution. We admit it is difficult to estimate the true PGV distribution only from the fault distance and surface soil information, but this method characterizes PGV of most of the near-source stations.

It is difficult to determine the dip angle of the fault surface from strong motion records only[10]. We tried to compute the PGV_a from east- and west-dip fault surfaces, and the west-dip fault surface showed the better correlation to the observed PGV (see Figure 7). Therefore, we use west-dip fault surface in this paper.

4.2.PGV Estimation from the relationship between observed records and damage rank of main hall of temples and shrines

The damage ratio of main hall of temples and shrines are shown as circles in Figure 1. Severely damaged buildings (D3-D5) are distributed in the area from downtown Kashiwazaki to Kariwa. This area corresponds to the dimension of the Kashiwazaki basin, which suggests that the entire basin was subjected to strong shaking. In the severely damaged area, foundation damage, soil deformation, and sand injection due to the liquefaction were also observed. The records of the K-NET Kashiwazaki and KKNPP have the predominant period of 2 seconds, and this frequency content caused the severe building damage.

In this section, we estimate PGV from the relationship between observed records and damage rank of main hall of temples and shrines constructed in the section 3.2. PGV was estimated by the following procedure: First, the D3 damage ratio (the ratio of the damaged buildings subjected to damage of greater equal to D3 level against the total buildings) of 2km radius neighborhood of a surveyed main hall is calculated for all surveyed sites. This damage ratio is substituted into the inverse function of equation (2) to estimate PGV. If the D3 damage ratio is 0%, it is removed from the analysis since the value does not exist in the lognormal distribution theoretically. There was no site with D3 damage ratio 100%. We removed the sites with samples less than 5 within 2km. We also tried 1km radius to compute the D3 damage ratio for more sensitive estimation. However, the resolution was not enough since the number of the samples in the neighborhood was too few. Therefore, we use the radius of 2km. Since the sedimentary soil structure in this region is very complicated, there is a limitation to characterize the local change, but it is helpful to understand the perspective of the ground motion distribution in this region.

The comparison between the PGV estimated by this method (we call this PGV_t) and the PGV_a in section 4.1 is shown in Figure 8. In this figure, “o” and “x” symbols represent surveyed sites with altitude less than or greater than 10m, respectively. The correlation coefficient between the PGV_t and PGV_a is 0.65. The PGV_t and PGV_a show good agreement in the low altitude region (i.e. Kashiwazaki basin), but there is a large discrepancy in the region which has large altitude gradient. This region is a severely damaged area, where many totally collapsed wooden houses were observed in our field survey. One of the reason why the PGV_a in this region underestimate PGVt is, that the soil amplification factor is small due to the short distance to the mountains and hills (In the empirical equation of Matsuoka et al.,[13] ARV becomes small as the distance to the mountains and hills becomes short).

Figure 9 shows the PGV_a distribution and PGV_t at our survey sites. Most of the sites, the PGV_t and PGV_a agree well. The downtown Kashiwazaki where PGV larger than 100cm/s was recorded, shows large PGV_t and PGV_a, which agree with the observed records.

4.3. PGV Estimation from the empirical function of the ratio of overturned tombstones

In section 3.3, overturned tombstone data in the station neighborhood shows the ratio of the overturned tombstone does not fit the empirical function of the ratio of overturned tombstones. In order to check the effect of the geographical condition to the applicability of this function, we apply the empirical function of Kaneko and Hayashi to all of surveyed sites, and compare with the PGVa. The sites with 0% or 100% of overturned tombstones are removed from the analysis since the value does not theoretically exist in the lognormal distribution.

Figure 10 shows the PGV_a distribution and PGV estimated from the ratio of overturned tombstones (we call this PGV_b) at our survey sites. PGV_b underestimates PGV_a especially in the Kashiwazaki basin. K-NET Kashiwazaki and Kariwa observed PGV of 110-120 cm/s and PGV_a around the station is compatible with the observation. However, the PGV_b is less than 80cm/s, which cannot characterize the real ground motion.

This result shows the PGV obtained from the ratio of overturned tombstones does not agree with the observed PGV, especially in the Kashiwazaki basin where the long period ground motion was amplified. Also, the PGV estimated from the ratio of overturned tombstone becomes smaller than PGV estimated from attenuation relationship in the Kashiwazaki basin. The effect of the long period ground motion (longer than 1 second) to the tombstone is not clear in this analysis. The relationship between the ratio of overturned tombstone and long period ground motion needs to be examined in the future work.

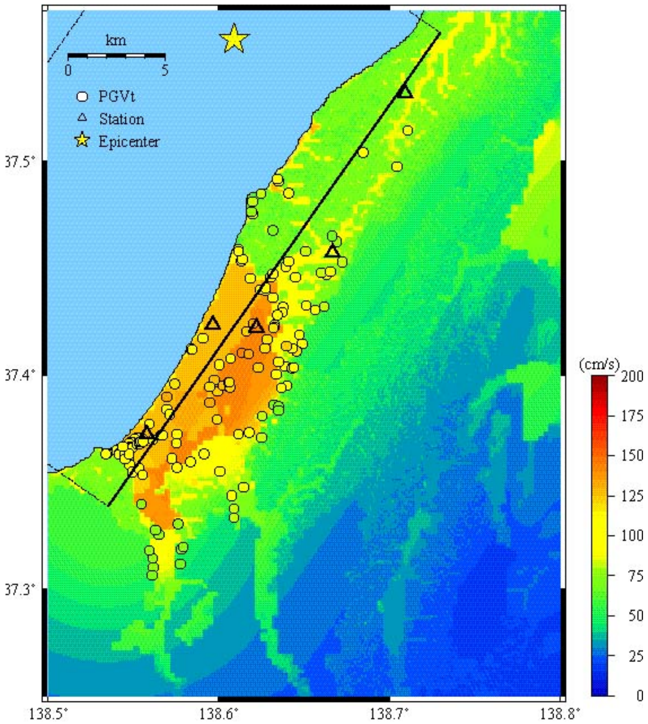

Figure 9 PGV_a distribution and PGV_t (in circle).

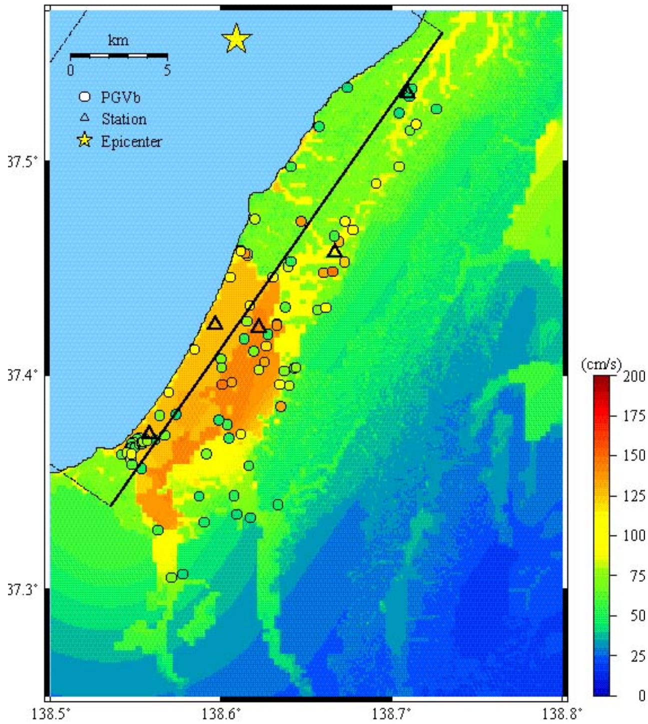

Figure 10 PGV_a distribution and PGV_b (in circle).

5. CONCLUSION

In this paper, we performed a damage survey of temples and shrines near the source region of the 2007 Niigata-ken Chuetsu-oki earthquake and tried to estimate the distribution of strong ground motions from the damage rank of main hall of temples and shrines. Our conclusions are as follows:

- We compared the observed records and damage ratio of main hall of temples and shrines, and shows the damage ratio has a good correlation with PGV. Based on this result, the empirical function to estimate PGV from damage ratio for the 2007 Niigata-ken Chuetsu-oki earthquake was proposed. Defining the ratio of the damaged buildings subjected to D3 - D5 damage against the total buildings as P_{D3} damage ratio, the relationship between $P_{D3}$and PGV is; $P_{D3}(PGV) = \Phi(\ln(PGV)-4.61)/0.31)$
- The PGV distribution in the entire near-source region was estimated from the constructed empirical function of PGV and damage ratio of main hall of temples and shrines. The result shows the PGV exceeds 100cm/s in most of the Kashiwazaki basin.
- The PGV_t estimated from the damage rank of main hall of temples and shrines agrees with PGV_a in the most part of the near-source region, but PGV_a becomes smaller than PGV_t in the region which has large altitude gradient.
- Using the empirical function between the PGV and ratio of the overturned tombstones, we estimated the PGV from the tombstone damage and compared with the observed PGV. The estimated PGV does not agree with the observations since the predominant frequency of some stations exceeds 1 second in the 2007 Niigata-ken Chuetsu-oki earthquake.
- The PGV estimated from the ratio of overturned tombstone becomes smaller than PGV estimated from attenuation relationship in the Kashiwazaki basin. The effect of the long period ground motion (longer than 1 second) to the tombstone is not clear in this analysis. The relationship between the ratio of overturned tombstone and long period ground motion needs to be examined in the future work.

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