Estimation of Strong Motion during the 2011 Northern Nagano Earthquake and an Associated Building Damage Survey

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SUMMARY:
We conducted a damage survey of the wooden structures and collected very dense ambient noise measurements in the near-source region of the 2011 Northern Nagano earthquake in central Japan. The percentage of totally collapsed buildings exceeded 30% in the Aokura and Yokokura colonies of Sakae village, Nagano prefecture. The percentage in the Mori colony, where a strong motion was recorded during the mainshock, was less than 10%. We estimated the strong motion in the Aokura and Mori colonies from the ambient noise measurements and strong motion records. The estimated strong motion distribution reflects the soil conditions and varies within that small area. The correlation of the estimated strong motion and damage ratio of the wooden structures is reasonably high, which indicates that the estimated ground motions are realistic. The damage curve obtained in this research shows that the collapse ratio exceeds 50% at around 150 kine of input ground motion.

Keywords: Building damage survey, Wooden structure, Strong motion, Ambient noise, H/V spectrum

1. INTRODUCTION

The 2011 Northern Nagano earthquake, which occurred on March 12, 2011, produced strong shaking in the northern part of the Nagano prefecture, located in the central region of Honshu Island, Japan. However, because the earthquake occurred on the day following the great Tohoku earthquake, public attention was very low. The largest seismic intensity was 6 upper (X-XI in MMI scale) in Sakae village, Nagano prefecture, and the largest peak ground velocity exceeded 110 cm/s. Sakae village is located between mountains, and the local settlements are very sparse. Therefore, it is important to understand the differences in the structural damage and the distribution of strong motions during the earthquake. We conducted a damage survey of the wooden houses in Sakae village in Nagano prefecture and Tsunan town in Niigata prefecture, both of which are located above the fault surface. We also performed a very dense ambient noise measurement in Sakae village and estimated the distribution of the strong motions during the earthquake on the basis of the strong motion record and ambient noise records. In this paper, we present a relationship between the estimated ground motions and damage ratio of the wooden houses, and compare this damage curve with those obtained from past earthquakes.

2. THE 2011 NORTHERN NAGANO EARTHQUAKE AND STRONG MOTION RECORDS

The 2011 Northern Nagano earthquake occurred at 3:59 a.m. on March 12, 2011. The focal depth was 8 km, the JMA magnitude was 6.7, and the largest seismic intensity was 6 upper in Sakae village (Japan Meteorological Agency, 2011). The fault rupture surface estimated from the aftershock distribution is north-west dipping, and the surface has dimensions of 10 × 20 km (Figure 1).

Near-field strong motion records at the town hall of Sakae village were recorded by the government of the Nagano prefecture and are available at the website (Earthquake Research Institute, 2000). Figure 2 shows the acceleration and velocity waveforms recorded during the mainshock. The sensor recorded ground acceleration, and we processed the original record using the following procedure. First, we removed the DC offset from the data, applied a baseline correction scheme proposed by Boore (Boore, 2001), and integrated once in the time domain to obtain the velocity record. The acceleration records of both the EW and NS components exceed 900 cm/s^2, and the peak ground velocity of the EW component exceeds 110 cm/s. Figure 3 shows the acceleration response spectrum of the recorded data with a 5% damping factor. The EW component has a large peak at 0.9 s, which is close to the period (1–2 s) which causes the most damage to wooden structures (Sakai et al., 2006). Based on these results, the recorded ground motion close to the source was likely to cause significant damage to wooden structures.

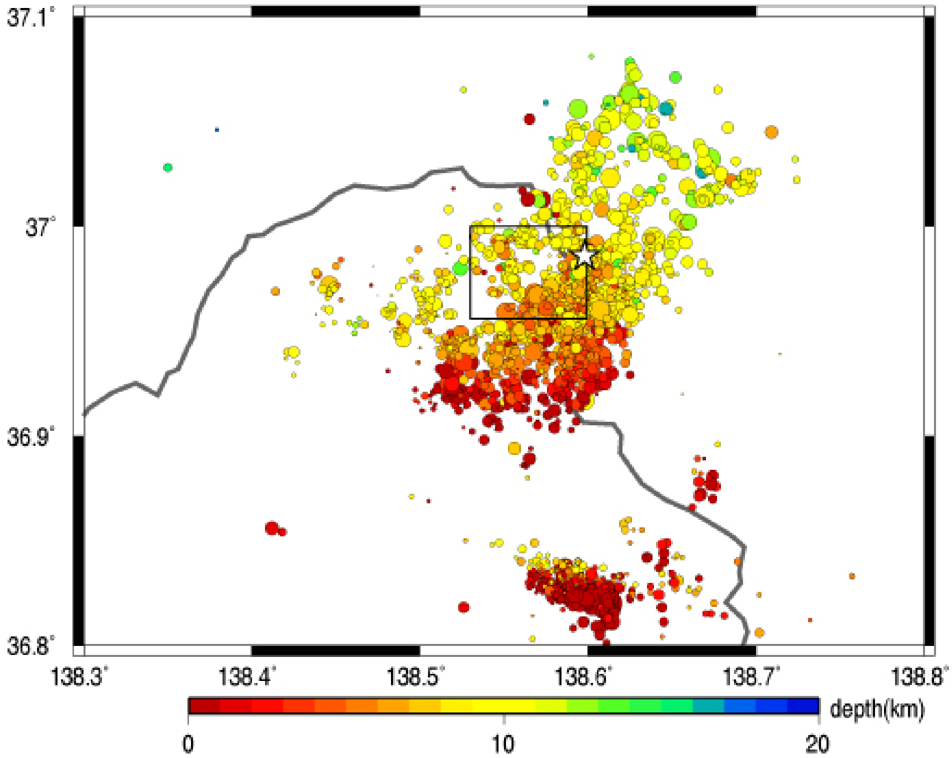

Figure 1. Seismicity for the period March 1–31, 2011, obtained from the JMA unified catalog. The color of the circles shows the depth of the hypocenters. The rectangle in the center shows the area that is enlarged in Figure 4, and the star symbol shows the epicenter of the mainshock. The thick gray line shows the boundary between Nagano and Niigata prefectures.

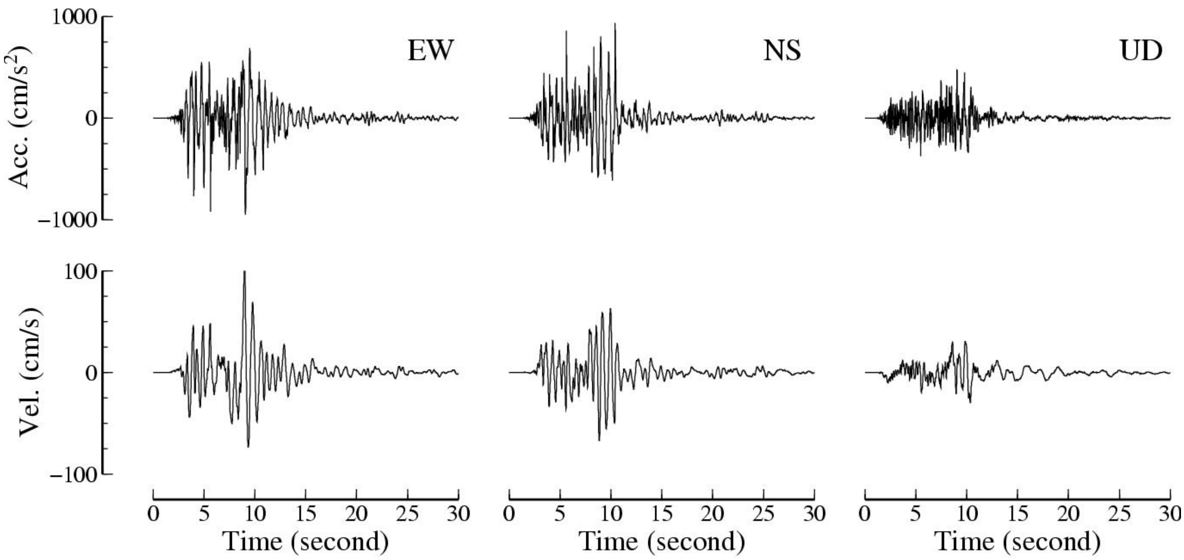

Figure 2. Strong motion record of the mainshock recorded at the strong motion station in Sakae village. Top: acceleration waveforms, bottom: velocity waveforms. EW, NS, and UD components from the left.

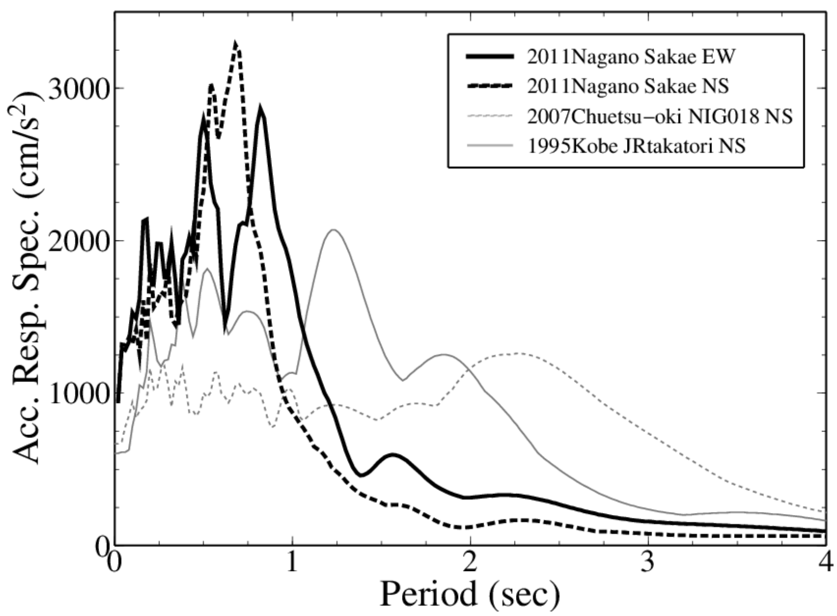

Figure 3. Acceleration response spectrum of the waveform recorded in Sakae village, K-NET Kashiwazaki for the 2007 Chuetsu-oki earthquake, and JR Takatori for the 1995 Kobe earthquake (all measurements have a 5% damping coefficient).

3. FIELD SURVEY

3.1. DAMAGE SURVEY OF WOODEN STRUCTURES

The field survey was performed on June 6–9, 2011, 3 months after the mainshock. The survey area spans the north-east area of Sakae village (the 7 colonies are Mori, Aokura, Yokokura, Kotaki, Tsukioka, Minotsukuri, and Yukitsubo) and the north-west area of Tsunan town (the 5 colonies are Hanekura, Teraishi, Sakamaki, Kameoka, and Kodane). The size of the surveyed area is about 5 km in the east-west direction and 3 km in the north-south direction. Figure 4 shows the location of the target area. The fault surface is much larger than the survey area, and it encompasses all of the survey area.

We performed the survey in three groups, with two people in each group. The grade of the damage was judged according to the damage pattern chart for wooden structure proposed by Okada and Takai (1999). The criteria are D0 (no damage), D1, D2 (minor damage), D3 (half collapsed), and

D4, D5 (totally collapsed). We visually investigated the damage and recorded damage levels on the local house map. We also recorded the usage of the structures (house, store, office, storage, etc.) and the type of the structures (wood, steel, RC, etc.). There were structures already cleared when we carried out the survey. We treated those structures as totally collapsed because we can assume that they were damaged beyond repair. The total number of structures we surveyed was 880.

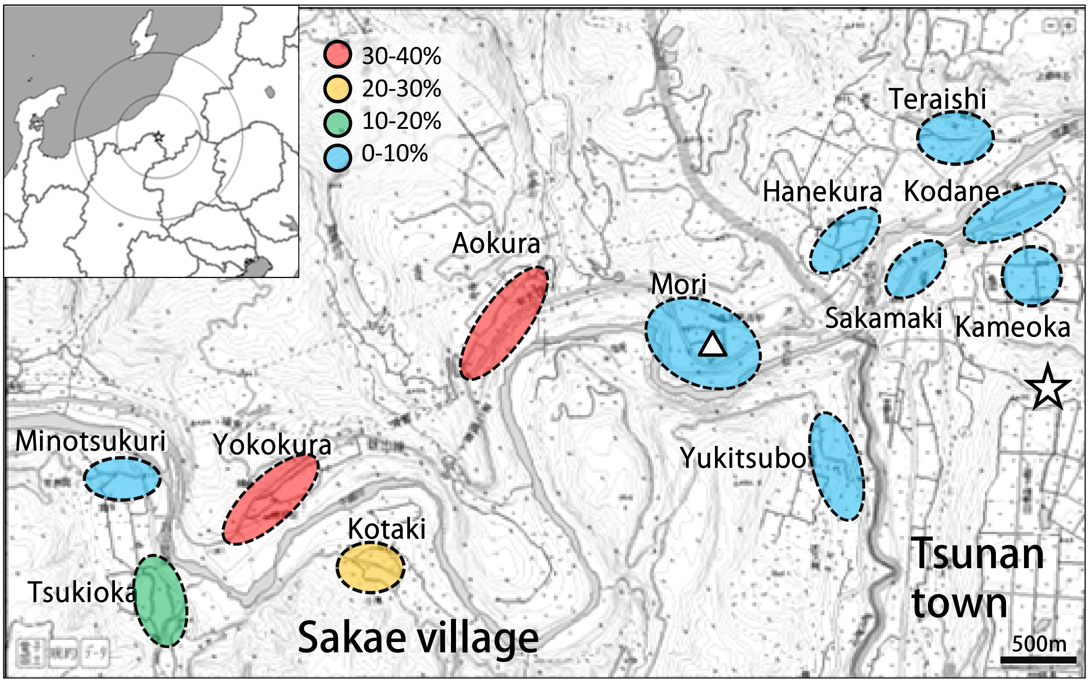

Figure 4. Damage ratio of totally collapsed houses. Aokura and Yokokura colonies show more severe damage. The triangle in Mori colony shows the strong motion station, and the star shows the epicenter.

Table 1. Damage ratios of wooden houses and results of ambient noise measurements in each colony. The damage ratio is in percentage.

No	Colony	Location	House			House + Store			Longitude	Latitude	H/V	PGA	PGV	JMA SI
			D4-D5 (%)	D3-D5 (%)	N	D4-D5 (%)	D3-D5 (%)	N			(Hz)	(cm/s^2)	(cm/s)	
1	Mori	Seismic Station	5.4	18.9	74	11.6	26.3	95	138.577	36.988	2.64	947	111	6.41
2	Aokura	Center	32.3	46.2	65	33.8	47.1	68	138.564	36.990	1.86	1962	216	7.14
3	Yokokura	Center	30.6	61.1	36	31.7	61.0	41	138.551	36.981	3.27	1104	99	6.59
4	Yokokura	Damaged area	30.6	61.1	36	31.7	61.0	41	138.548	36.979	2.93	1427	142	6.86
5	Kotaki	Center	21.1	52.6	19	20.0	55.0	20	138.557	36.977	5.25	2247	118	6.7
6	Tsukioka	Center	13.0	46.3	54	12.3	45.6	57	138.544	36.975	6.57	946	91	6.34
7	Tsukioka	Damaged area	13.0	46.3	54	12.3	45.6	57	138.543	36.976	4.66	1124	103	6.46
8	Minotsukuri	Center	3.6	16.1	56	6.5	17.7	62	138.541	36.981	9.13	1105	106	6.59
9	Minotsukuri	Damaged area	3.6	16.1	56	6.5	17.7	62	138.540	36.982	5.86	1141	110	6.6
10	Yukitsubo	Center	0.0	12.5	16	0.0	22.2	18	138.586	36.981	2.95	636	80	6.27
11	Hanekura	Center	2.6	15.4	39	2.5	15.0	40	138.584	36.993	3.05	1096	107	6.6
12	Teraishi	Center	3.7	25.9	27	3.3	23.3	30	138.592	36.998	6.74	815	82	6.32
13	Sakamaki	Center	0.0	0.0	35	0.0	0.0	44	138.588	36.991	3.00	811	81	6.23
14	Kodane	Center	0.0	15.8	19	4.2	20.8	24	138.595	36.995	4.27	823	87	6.29
15	Kameoka	Center	7.4	14.8	27	7.1	14.3	28	138.595	36.990	1.90	1330	92	6.42

3.2. DENSE AMBIENT NOISE MEASUREMENT

We also performed an ambient noise measurement to evaluate the subsurface structure. We used JU210 sensors made by Hakusan, and performed the measurement for 11 min at each site. JU210 includes 3 components acceleration-type sensor, logger, and battery, in a casing. The sampling frequency was 100 Hz and the cut-off frequency of the high-cut filter was 30 Hz. Measurements for the survey were taken at 40 m increments in the Aokura and Mori colonies, Sakae village. Typical 1–2 sites were measured in each of the other colonies. The peak frequencies of the H/V spectra of the ambient noise in each colony are shown in Table 1.

4. RESULT OF THE DAMAGE SURVEY AND ESTIMATION OF STRONG MOTIONS

4.1. DAMAGE RATIO OF THE WOODEN STRUCTURES

The damage ratio of the wooden structures in each colony was computed based on the building damage survey. In this analysis, the target structure type is wooden houses only. All other types of structures are excluded. We computed the percentage of totally collapsed houses (D4 or D5) and partially and totally collapsed houses (D3, D4, and D5). The percentage of totally collapsed houses in each colony is shown in Figure 4. The percentage of totally collapsed houses in the Aokura and Yokokura colonies of Sakae village exceeds 30%. This damage ratio is higher than that of the most damaged area during the 2007 Noto Hanto earthquake (Hashiride colony in Monzen town: 25%, Arai et al., 2008). Because the percentage of totally collapsed houses in Mori colony, where the strong motion was recorded during the mainshock, is less than 10%, the strong motion in the Aokura and Yokokura colonies may have been larger than the recorded strong motion. We also computed the percentage of totally collapsed houses and commercial buildings (stores and office buildings), as shown in the Table 1. The percentages of damaged buildings are slightly changed, but the overall pattern of the damage grades in the colonies does not change.

In order to compare damage with the site condition estimated from the ambient noise measurement completed later, the damage ratio at the sites of the ambient noise measurements were computed in the Aokura and Mori colonies. Because the ambient noise measurement was performed in a very dense spacing, we needed to identify the damage profile of the buildings near the survey site. However, if we compute the damage ratio from a small area, the variance becomes large because the number of samples in the area is insufficient. To solve this trade-off, we introduce a weighting as a function of the distance between the site of the ambient noise measurement and each building (R_i), then computed the percentage of the damaged houses within 100 m of the site of the ambient noise measurement.

$$\text{Damage Ratio } (DR_{Dx}) = \sum_{i=1}^{n} w_i f_i \Big/ \sum_{i=1}^{n} w_i \times 100 \tag{4.1}$$

where

f_i = 1, if the damage to building *i* is greater equal to D3/D4
= 0, if the damage to building *i* is smaller than D3/D4

w_i = 1/ R_i, if R_i is greater equal to 0.02 km
= 1/0.02, if R_i is less than 0.02 km

n = number of the houses within 100 m of the site of ambient noise measurement.

The damage ratio with the threshold of D3 is defined as DR_{D3}, and the ratio with the threshold of D4 is defined as DR_{D4}. By applying the weighting, we can put emphasis on the damage profiles of the buildings near the site of the ambient noise measurement. We eliminated 11 points where number of the houses within 100 m was less than 10. The estimated damage ratio (DR_{D4}) is shown in Figure 5. The center of the Aokura colony and the north-east area of the Mori colony showed the larger damage ratio. The north-east area of the Mori colony is next to the cliff to the Chikuma river, and that area was affected by a landslide due to the strong motion. We think this ground movement was an additional factor on the level of structural damage in this area, so the 4 points in the north-east area of the Mori colony were excluded from the following analysis (see Figure 5).

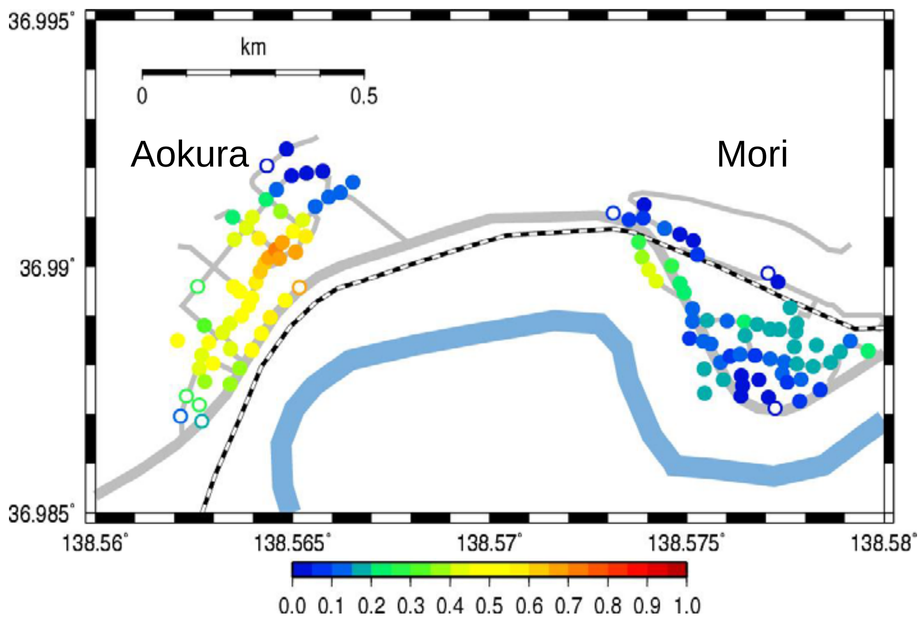

Figure 5. Damage ratio of totally collapsed houses at the ambient noise observation sites in Aokura and Mori colonies. The damage ratio is higher in the center of Aokura colony and north-western part of Mori colony. The open circles show a site with samples less than 10.

4.2. ESTIMATION OF THE STRONG MOTION BASED ON AMBIENT NOISE MEASUREMENTS

The H/V spectrum at a site is computed from the ambient noise record. The H/V spectrum was computed using the following method. First, 5 segments with 4096 points (40.96 s) were randomly selected from the 11 min record and the Fourier amplitude spectrum of each segment was computed. We repeated this selection 100 times, and a set of the 5 spectra with the smallest variance were selected. The horizontal component is defined as the root mean square of two components. We smoothed the spectra with a smoothing filter, Parzen window at 0.05 Hz. Table 1 shows the peak frequency of the H/V spectrum in each colony. Figure 6 shows a typical H/V spectrum in the Aokura and Mori colonies, and Figure 7 shows the distribution of the peak amplitude and frequency in the Aokura and Mori colonies. The H/V spectra in the Aokura and Mori colonies are quite different, and the H/V spectrum in the Aokura colony has a larger peak and lower peak frequency.

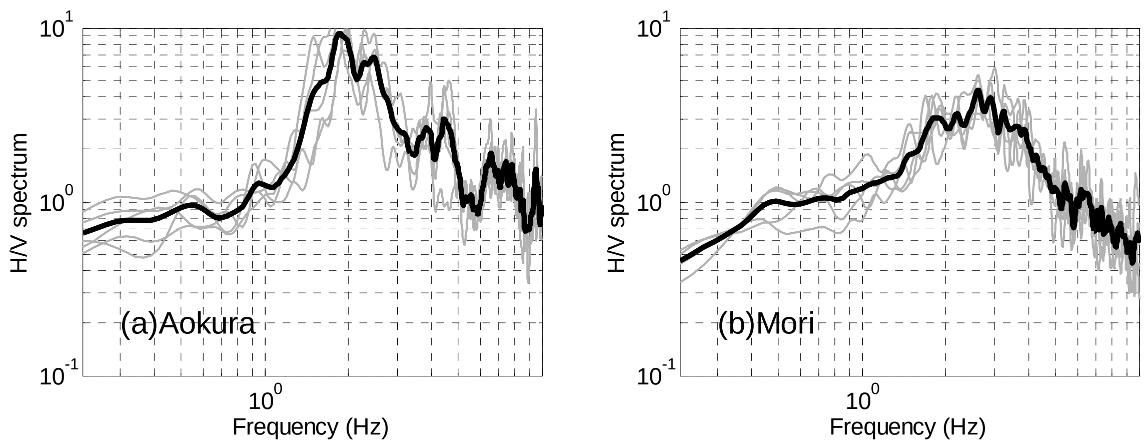

Figure 6. Typical H/V spectra of ambient noise in Aokura and Mori colonies. The thin lines show the spectra of 5 segments, and the thick line shows the mean spectrum of 5 segments.

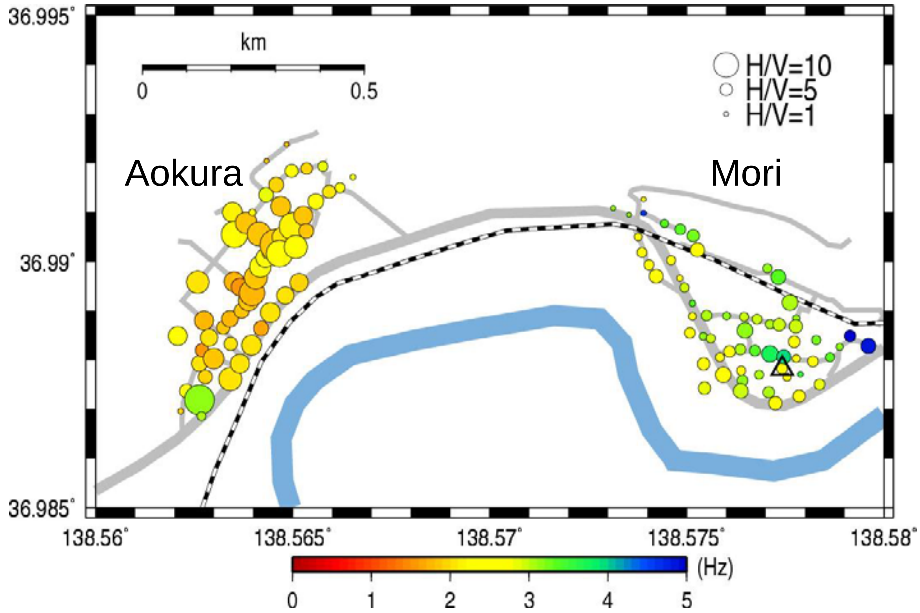

Figure 7. Peak amplitudes and peak frequencies of the H/V spectrum in Aokura and Mori colonies. The size of the circle shows the peak amplitude, and the color of the circle shows the peak frequency. The triangle shows the location of a strong motion station.

We estimated the strong motion records at the sites of ambient noise measurement during the mainshock from the H/V spectra and the strong motion recorded in the Mori colony. Because the sites of ambient noise measurement and the strong motion station are only 1.2 km away at the maximum, we assumed that the input ground motion in the seismic bedrock is identical and obtained the estimated ground motion from the following equation:

$$A(\omega) = A_0(\omega)\times AMP(\omega)/AMP_0(\omega) \quad (4.2)$$

where $A_0(\omega)$ and $A(\omega)$ are the Fourier amplitude spectra of the acceleration records at the strong motion station and the site of the ambient noise measurement, respectively, and $AMP_0(\omega)$ and $AMP(\omega)$ are the site amplification response between seismic bedrock and ground surface at the strong motion station and site of the ambient noise measurement, respectively. That means that the strong motion record during the mainshock is corrected by the ratio of the site amplification response between the strong motion station and site of the ambient noise measurement.

The ratio of the site amplification response between the strong motion station and site of the ambient noise measurement was computed by the method proposed by Nagao et al. (2010). There are still arguments about the theoretical interpretation of the H/V spectrum, but Nagao et al. (2012) explained that ambient noises are composed of a mixture of the surface wave and body wave. Based on their interpretation, this correction scheme assumes that there is a correlation between the amplitude of the H/V spectrum and site amplification. We use the spectrum of the original strong motion data in the long-period component for the correction because the long-period component is sometimes contaminated by the noise of the H/V spectrum. To be more precise, we multiplied by 1 if the period was longer than 2 s, multiplied by the correction coefficient obtained by the approach in Nagao et al. (2010) if the frequency was less than 1 s, and connected those two ranges by a smooth cosine curve.

The strong motion record of the mainshock at the strong motion station includes the nonlinear effect of the subsurface soil structure. In this correction scheme, the difference in nonlinear effect at each site is not considered, and the same nonlinear effect is assumed for each ambient noise survey point. This assumption may not be true, so it is our future work to evaluate the nonlinear effect. Here, we corrected the amplitude of the spectrum only, but did not correct the nonlinearity and phase characteristics.

Figure 8 shows the estimated peak ground acceleration (PGA) and peak ground velocity

(PGV) at the sites of the ambient noise measurement. In this paper, the largest component of the two horizontal components is used for the PGA and PGV. In the Aokura colony, the center area shows a larger ground motion. This is consistent with the distribution of damaged wooden houses. The ground motion distribution in the Mori colony shows smaller variation than that in the Aokura colony.

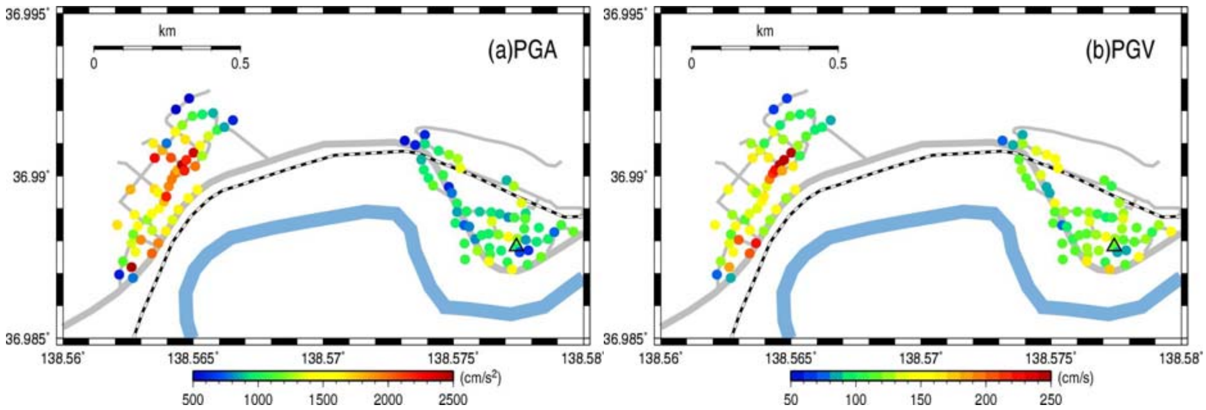

Figure 8. Estimated PGA and PGV during the mainshock. The triangle shows the location of a strong motion station.

5. DISCUSSION

In this section, the estimated strong motion during the mainshock and damage ratio in the Aokura and Mori colonies are compared. Figures 5 and 8 show a similar distribution. For example, the center of the Aokura colony shows large damage ratios for wooden houses and large amplitudes of estimated ground motions. In order to compare them precisely, in Figure 9 we plotted the relationship between the PGA/PGV and the damage ratio of the wooden houses. The estimated ground motion and damage ratio in the Aokura colony show a larger variation than those in the Mori colony. This implies that the site condition in the Mori colony has smaller variations, which made the distribution of the damage ratio homogeneous, while the center of the Aokura colony has a large site amplification, which caused severe damage to the wooden houses. Although the damage level of the wooden houses is affected by variation in the seismic performance of each structure, the average of the damage ratio reflects the amplitude of the ground motions. Therefore, the good correlation between the estimated ground motions and damage ratio of the wooden structures implies that the estimated ground motion is substantially reasonable.

The relationship between the damage ratio of the wooden houses and estimated ground motions is regressed as a function of the cumulative Gaussian distribution function, Φ. Because both the damage ratio of the wooden houses and the estimated ground motions include the estimation error, we obtained the regression equation by the orthogonal regression. The most probable regression equations that can explain the dataset are as follows:

$$\text{PGA: } DR_{D3} = \Phi[(\ln(PGA)-7.276)/0.551] \quad (5.1)$$
$$\text{PGV: } DR_{D3} = \Phi[(\ln(PGV)-4.978)/0.393] \quad (5.2)$$
$$\text{PGA: } DR_{D4} = \Phi[(\ln(PGA)-7.491)/0.535] \quad (5.3)$$
$$\text{PGV: } DR_{D4} = \Phi[(\ln(PGV)-5.133)/0.381] \quad (5.4)$$

The ground motions resulting in a 50% damage ratio of totally collapsed buildings are 1792 cm/s^2 for the PGA, and 170 cm/s for the PGV. These hazard curves are compared with those obtained from the damage of past major earthquakes (Murao and Yamazaki, 2002; Hayashi 2004; Sakai et al., 2006; Yamada et al., 2008). The hazard curves and the samples of the PGVs and damage ratios are shown in Figure 10. The results for the northern Nagano earthquake show a smaller damage ratio than the 1995 Kobe earthquake, but a slightly larger one than the 2000 western Tottori and 2004 Niigata-ken

Chuetsu earthquakes. Sakae village has very heavy snowfall during winter (more than 3 m high), and the necessity of maintaining the houses to survive that level of snowfall may have resulted in the higher seismic performance. The hazard curve obtained from this research shows that a PGV of 150 cm/s is a threshold for severe damage to wooden houses.

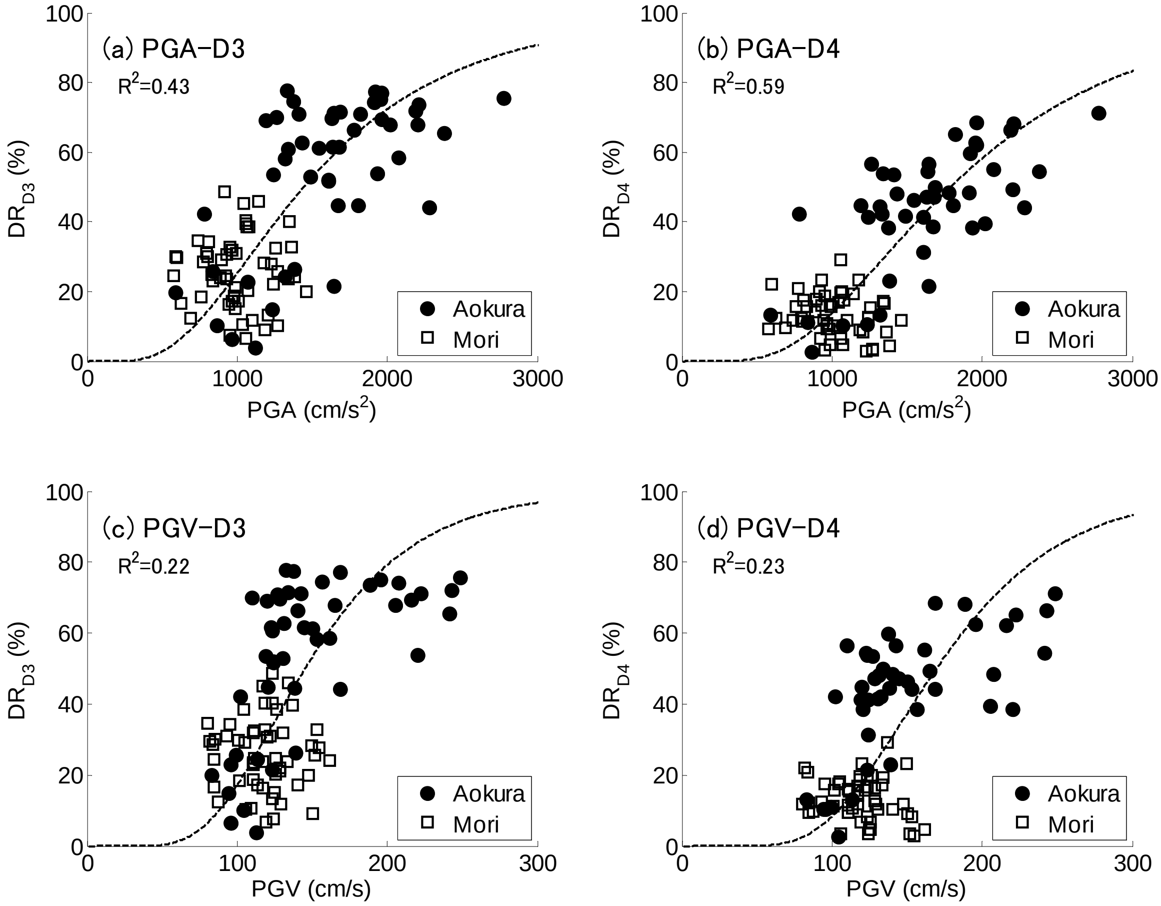

Figure 9. Relationship between the damage ratio of wooden houses (DR_{D3} and DR_{D4}) and estimated PGA/PGV. Solid circles show the data in Aokura colony, and open squares show the data in Mori colony. The regression curve, which explains the relationship the best, is also added. R^2 is the coefficient of determination.

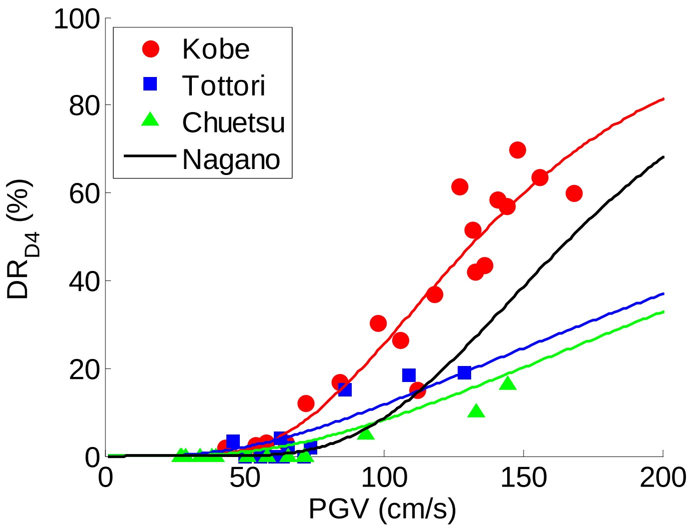

Figure 10. Vulnerability curves (relationship between the damage ratio of wooden houses and PGV) for the past earthquakes.

6. CONCLUSIONS

In this paper, we conducted a damage survey of wooden structures and collected very dense ambient noise measurements in the near-source region of the 2011 Northern Nagano earthquake in central Japan. The percentage of totally collapsed buildings exceeded 30% in the Aokura and Yokokura colonies of Sakae village, Nagano prefecture. The percentage in the Mori colony, where a strong motion was recorded during the mainshock, was less than 10%. We estimated the strong motion in the Aokura and Mori colonies on the basis of the ambient noise measurements and strong motion records. The estimated strong motion distribution reflects the soil conditions and varies within the small area studied. The correlation of the estimated strong motion and damage ratio of the wooden structures is reasonably high, which indicates that the estimated ground motions are realistic. The damage curve obtained from this research shows that the collapse ratio exceeds 50% at around 150 kine of input ground motion.

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