Damage Ratios and Ground Motion Characteristics during the 2011 off the Pacific coast of Tohoku Earthquake

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SUMMARY:
The fragility curve during the 2011 off the pacific coast of Tohoku earthquake was discussed based on the damage ratios (DRs) and ground motion characteristics, such as peak ground acceleration (PGA), peak ground velocity (PGV), and so on. It was found that the DRs were related with ground motion characteristics during this earthquake. Generally, the DRs were smaller than those during the 1995 Kobe earthquake for a certain level of ground motions, PGA of more than 450 gal and PGV of more than 80 cm/s. However, at some districts the DRs did not correspond to suitable levels of ground motion characteristics. The reason was that the ground motions at the strong motion stations did not always represent those at the damaged sites. The ground motions at one damage site were estimated using the H/V spectral ratio of microtremors and strong motions observed near the damaged site.

Keywords: damage ratio, ground motion characteristics, H/V spectral ratio of microtremors

1. INTRODUCTIONS

The 2011 off the Pacific coast of Tohoku earthquake on March, 11, 2011 with Mw9.0 was one of the most disastrous mega-thrust earthquakes in the history of Japan. The rupture was initiated approximately 100 km off-shore of Miyagi prefecture and extended about 450 km in length and about 200 km in width. This great earthquake has caused tremendous damage to infrastructures, lifelines and buildings along the coastline of the Tohoku and Kanto area. According to Fire and Disaster Management Agency (FDMA, 2012), more than one million buildings were collapsed, half-collapsed and partially damaged due to ground shaking and tsunami as of March, 13, 2012. The number of damaged buildings is still updated every other day, but tends to be stable gradually. The number of collapsed buildings caused by ground shaking in the inland areas was less than that for the other destructive earthquakes, such as the 1995 Hyogoken-Nanbu (Kobe) earthquake, the 1999 Taiwan Chi-Chi earthquake and the 2008 Wenchuan earthquake. Many studies (e.g., Miyakoshi, et al., 1997; Miyakoshi, et al., 2000; Yamazaki et al., 2000) on the relationship between damage ratios (DRs) and ground motion characteristics at the stricken districts have been carried out for the past destructive earthquakes. So far, the ground motions at the damaged sites have not been estimated adequately in those studies to clarify their relationships with building damage.

In this paper, at first, the damage ratio (DR) is defined as the ratio of the number of damaged buildings including collapsed, half-collapsed and partially damaged ones, to the total number of buildings in each district (an administrative unit, such as a city, or town). Next, the fragility curves during this earthquake are made based on the relationship between the DRs and ground motion characteristics obtained from the K-NET or KiK-net stations in the damaged districts. However, the ground motion characteristics at the K-NET and KiK-net stations do not represent those in the damaged districts because the stations were not near the damaged sites. Then we propose a method to estimate ground motions at the damaged sites using the underground velocity structures beneath the damaged sites and the observed ground motions at the stations near those sites. More accurate fragility curve is expected to be constructed based on the DRs and ground motion characteristics at the damaged sites, as long as the ground motions are correctly estimated at the damaged sites and non-damaged sites.

2. DATA SOURCE

During this earthquake, the buildings in the coastal districts were mainly damaged by tsunami over the Tohoku and Kanto areas. At the same time, in the inland districts, numerous buildings were damaged by ground shaking. The building damage statistics in the damaged districts, such as cities or towns, are published by the FDMA. Because our objective aims at the damage by ground shaking, the districts damaged by tsunami were excluded with the inundation maps provided by the Geospatial Information Authority of Japan (GSI).

Based on the damaged statistics, the DR is defined as Eqn. 2.1,

$$DR = (A + B + C)/D \times 100\% \tag{2.1}$$

i.e., the ratio of the sum of numbers of buildings including the collapsed (A), half-collapsed (B), and partially damaged ones (C) to the total number of buildings (D) in a district. Among them, D can be obtained from the Statistic Bureau of Ministry of Internal Affairs and Communications or the homepage websites of those districts. There are totally 82 damaged districts in six prefectures of Tohoku and Kanto areas studied in this paper.

The strong motion records at the K-NET and KiK-net stations were open to public soon after this earthquake. The observation records in 78 K-NET stations and 45 KiK-net stations are used to analyze the ground motion characteristics in this paper. In case where there was more than one observation station at a district, the ground motion characteristics observed are averaged arithmetically.

3. RELATIONSHIP BETWEEN DAMAGE RATIOS AND GROUND MOTION CHARACTERISTICS

3.1 The Fragility Curve

The fragility curve is usually used to examine the relationship between DRs and ground motion characteristics, such as peak ground acceleration (PGA), peak ground velocity (PGV), spectral intensity (SI) and JMA seismic intensity (I_{JMA}). In this paper, the cumulative probability of building damage-DR is assumed as Eqn.3.1,

$$DR = \Phi((x - \lambda)/\xi) \tag{3.1}$$

where, Φ is cumulative standard normal distribution function, x is a variable with respect to ground motion index, such as I_{JMA}, natural logarithm of PGA, PGV, or SI. λ and ζ are the mean and standard deviation of x, and are determined by the least squares method. The PGA, PGV and SI are the larger value between NS and EW components.

At the K-NET station-Tsukidate of Kurihara city, the Japan Meteorological Agency (JMA) seismic intensity (I_{JMA}) scale reached the highest-7, its peak ground acceleration (PGA) was 2933 gal, and its duration was about 300 s during this earthquake. Motosaka (2011) pointed out that the large ground motion record at the Tsukidate station in the Kurihara city may be due to partial uplifting of the foundation of the instrument, so the corresponding ground motion indices at this station were excluded in the analysis of fragility curve. Fig. 3.1 shows the fragility curves of DRs and the ground motion indices, i.e. PGA, PGV, I_{JMA} and SI, with solid lines. The coefficients for fragility curve and the determination coefficient R^2 which is used to assess the goodness of fit are all given in Table 3.1. The relationship between DRs and PGV made the smallest standard deviation and the largest determination coefficient among all of other relations, indicating that DRs have the best correlation with PGV. DRs also correlate well with SI and I_{JMA}, but the correlation between DRs and PGA is not so well. The standard deviations of those fragility curves are large and the determination coefficients are small in this earthquake, compared with the past studies about fragility curves for other earthquakes (e.g., Yamaguchi et al., 1999; Midorikawa, et al., 2011). There were some districts where the level of ground motion characteristics is not so high, although the DRs were large. For example, the PGA and PGV at the strong motion station in the Yabuki town shown with green squares in Fig.3.1 are less than 500 gal and 50 cm/s, respectively, but the DR is quite large. The reason is that the ground motions at the observation stations do not represent those at the damaged sites, because they may be far away from one another.

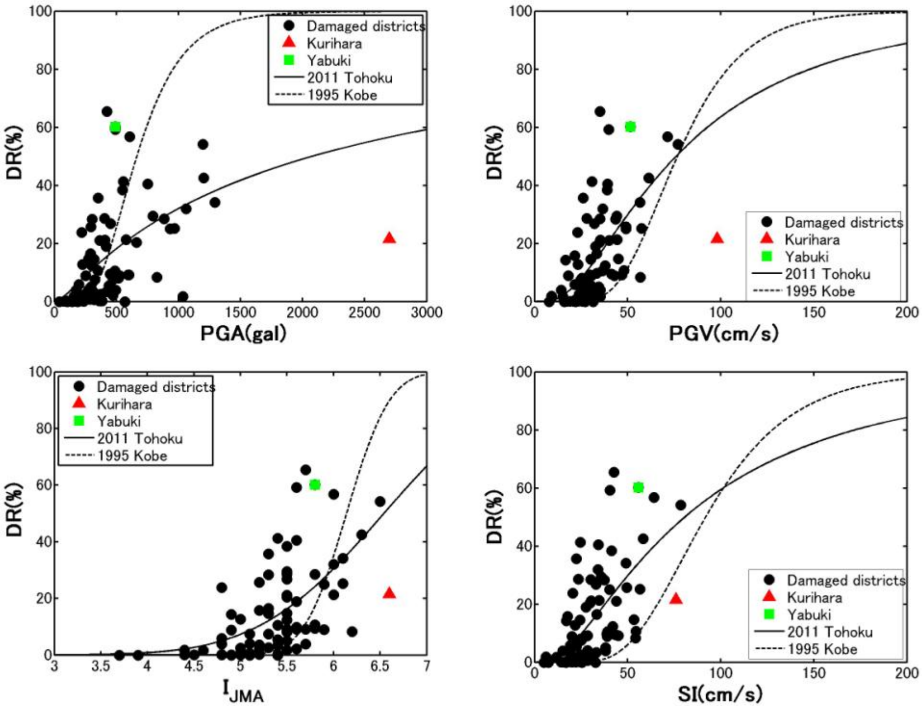

Figure 3.1. The fragility curves of DRs versus PGA, PGV, I_{JMA} and SI.

Table 3.1. The coefficients for the fragility curve (R^2 is determination coefficient)

	PGA(gal)	PGV(cm/s)	I_{JMA}	SI(cm/s)
λ	7.64	4.33	6.54	4.39
ζ	1.568	0.792	1.060	0.901
R^2	0.298	0.420	0.356	0.385

3.2 The Relationship of DRs versus PGA, PGV

Fig. 3.2 shows the relationship of DRs versus PGA, PGV. Equivalent predominant period-Teq is defined as Teq=2 π PGV/PGA. Here, the PGA and PGV is the maximum value of vector summation in three components. The DRs are divided into four levels, i.e. 0%≦DRs<10%, 10%≦DRs<20%, 20%≦DRs<30% and 30%≦DRs≦100%. It can be seen that the DRs ≧30% distribute in the equivalent predominant period range from 0.2s to 1.0s, PGV is larger than 25 cm/s and PGA 300 gal.

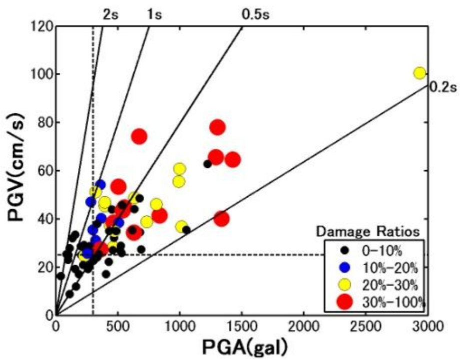

Figure 3.2. The relationship of DRs versus PGA, PGV. The solid lines show the equivalent predominant periods (Teq=2 π PGV/PGA; Teq=0.2s, 0.5s, 1.0s, 2.0s). The dotted lines are the thresholds of PGA and PGV for DRs ≧ 30%. Note that PGA and PGV is the maximum value of vector summation in three components.

3.3 Comparison with 1995 Kobe Earthquake

Many studies on the fragility curves for the past destructive earthquakes (e.g. Miyakoshi, et al., 2000; Midorikawa, et al., 2011; Wang, et al 2011) have been done based on the collapse ratio-CR (the ratio of number of collapsed and half-collapsed buildings to the total number of buildings). However, CR is so small in this earthquake that it is difficult to find a good correlation between CRs and ground motion indices. Fortunately, Yamaguchi (1999) analyzed the fragility curve with DRs versus ground motion indices in the 1995 Kobe earthquake. Then, the fragility curves of this earthquake are compared with those of the 1995 Kobe earthquake, as is shown in Fig. 3.1 with dotted lines. It can be seen that DRs are larger at the low levels of ground motions (e.g. PGA<450 gal, PGV<80 cm/s) in this earthquake, compared with those in the 1995 Kobe earthquake. It may be thought that the DRs include the numbers of partially damaged buildings which are much larger than those of collapsed and half-collapsed buildings. On the other hand, DRs in this earthquake are smaller at the high level of ground motions (e.g. PGA>450 gal, PGV>80 cm/s) than those in the 1995 Kobe earthquake. It can be explained through the property of response spectra.

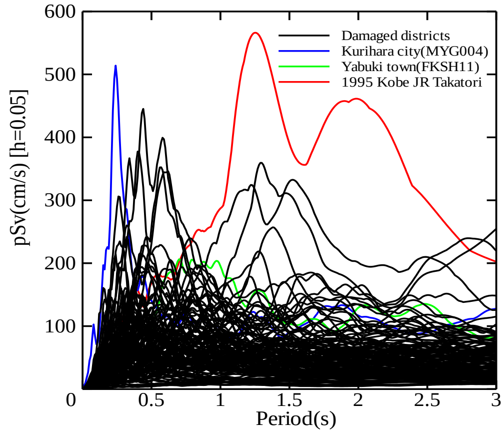

Figure 3.3. The pseudo-velocity response spectra (damping ratio h=0.05) of all the strong motion records used in this study and that of JR Takatori station in the Kobe earthquake.

Fig. 3.3 shows the pseudo-velocity response spectra-pSv (damping ratio h is 0.05) of strong motion records in the damaged districts during this earthquake and at the JR Takatori station during the 1995 Kobe earthquake. Obviously, the pSv's in most of the damaged districts during this earthquake are smaller in the period range between 1.0s and 1.5s, although they are higher in the period range shorter than 0.5 s. Sakai (2009) noted the period range of strong motions between 1.0 s and 1.5 s had closer relationship with seriously damaged buildings. Therefore, the smaller pSv's in this period range are the main reason for small DRs during this earthquake. The blue line in Fig. 3.3 shows the pSv at the

Tsukidate station of Kurihara city. Its pSv is very large in the period range shorter than 0.5 s and reaches the largest value at about 0.23 s, but the pSv in the 1.0 s-1.5 s period range is rather small. We can interpret the small DR in the Kurihara city even though the ground motion records were not amplified by partial uplifting of the foundation of the instrument. The green line in Fig.3.3 shows the pSv at FKSH11 in the Yabuki town. It can be seen that the pSv is not so large in the 1.0 s-1.5 s period range, but the DR is high shown in Fig. 3.3. The reason is attributed to the fact that the ground motions at FKSH11 do not represent for a whole damaged district.

4. ESTIMATION OF GROUND MOTIONS AT DAMAGED SITES

4.1 Methodology of Estimating Ground Motions at Damaged Sites

In general, the ground motion spectrum $O_i(f)$ on the surface at the i_{th} site can be expressed as the product of source spectrum $S_i(f)$, path spectrum $P_i(f)$ and transfer function $G_i(f)$ in Eqn. 4.1, or the product of input motion spectrum $B_i(f)$ and transfer function $G_i(f)$ in Eqn. 4.2.

$$O_i(f)=S_i(f)\cdot P_i(f)\cdot G_i(f) \tag{4.1}$$

$$O_i(f)=B_i(f)\cdot G_i(f) \tag{4.2}$$

Here, the transfer function is defined as the surface response to the input motion on the bedrock. Following the Eqn. 4.2, the input motion spectrum can be calculated from the ground motion spectrum divided by the transfer function, as is shown in Eqn. 4.3.

$$B_i(f)=O_i(f)/G_i(f) \tag{4.3}$$

Suppose that the observation station (i=0) and the adjacent damaged site (i=1) are not far away from each other, for example, less than 10 km, the input motion can be assumed to be the same, i.e. $B_0(f)= B_1(f)$, because the deeper structures are almost the same. Then the ground motion spectrum $O_1(f)$ at the damaged site can be estimated by means of input motion spectrum $B_0(f)$ at the observation station, as is shown in Eqn. 4.4.

$$O_1(f)= B_0(f)\cdot G_1(f) \tag{4.4}$$

Because the ground motion spectrum $O_0(f)$ is known at any observation stations, the input motion spectrum $B_0(f)$ can be easily calculated according to Eqn. 4.3 if the transfer function $G_0(f)$ is obtained. On the other hand, the transfer function $G_1(f)$ at the damaged site is needed to estimate the ground motions.

As the transfer functions depend on the underground velocity structures, it is essential to obtain the reliable S- and P-wave velocity structures. For a KiK-net station, the underground velocity structure can be obtained directly from the PS-logging data or identified from the spectral ratios of surface to underground (e.g. Saguchi, et al., 2009). However, when there are neither strong motion data nor PS-logging data at some damaged sites, the velocity structures are usually identified from the microtremor records based on the surface waves ellipticity (e.g. Arai and Tokimatsu, 2004; Fäh, et al, 2003; Yamamoto, et al, 2004). However, Kawase et al (2011) noted that the H/V spectral ratio for earthquake ground motions can be calculated theoretically as the amplitude ratio between transfer functions for S- and P-wave based on the diffuse-field theory, both calculated at the observation station with a coefficient depending on the bedrock. Further, they found that the earthquake H/V spectral ratio can be used to identify the velocity structures. Following Kawase’s viewpoint, we propose that the H/V spectral ratio of microtremors can also be used to identify the velocity structures, after confirming the consistency of H/V spectral ratios for microtremors and earthquakes.

The procedure for estimating ground motions at damaged sites is described as follows:

(a) Identifying the S- and P-wave velocity structures from the spectral ratios of surface to underground for small earthquakes at the KiK-net station.

(b) The H/V spectral ratio of earthquake ground motions is consistent with the theoretical H/V spectral ratio calculated with the identified S-wave and P-wave velocity structures from (a). In other word, the underground velocity structures can be identified from the earthquake H/V spectral ratio, which agrees with Kawase's idea.

(c) The H/V spectral ratios of microtremors are compared with those of earthquake. As long as the H/V ratios of the microtremors are approximately consistent with those of earthquakes, the velocity structures can be identified from the H/V spectral ratios of microtremors.

(d) The underground velocity structures at the damaged sites close to KiK-net stations are identified from the H/V spectral ratios of microtremors.

(e) We assume that the input motions on the bedrock at KiK-net stations are the same as those at the damaged sites.

(f) The ground motions at the damaged sites are estimated with the identified velocity structures including the S- and P-wave velocities in basement.

The estimation of ground motions mentioned above is implemented assuming that the soil layers behave linearly.

4.2 Case Study at one Damaged Site in the Yabuki Town

Yabuki town is situated in the south area of Fukushima prefecture. The DR at the Yabuki town is 60.2%, PGA, PGV, I_{JMA} and SI are 492.3 gal, 51.4 cm/s, 5.8 and 55.6 cm/s, respectively, during this earthquake, as has been shown in Fig. 3.1 with green squares. Fig. 3.1 shows that the DR is quite large although the ground motion indices are not so large. According to our field survey performed in the Yabuki town on July 10, 2011, the buildings near the KiK-net station-FKSH11 suffered minor damage, but collapsed and half-collapsed buildings were found easily at several damaged sites about 3 km far away from the KiK-net station. It suggests that the ground motions at FKSH11 cannot represent those at the damaged sites. Therefore, the ground motions at these damaged sites must be estimated in order to relate them with the DRs. As a case study, the ground motions at one damage site of Yamatouchi in the Yabuki town are estimated.

The underground velocity structure at FKSH11 in the Yabuki town is identified from the observed spectral ratio of surface to underground (-100.6 m deep) with the simulated annealing algorithm (e.g. Ingber, 1989; Saguchi, et al., 2009). To avoid the nonlinear effect on ground motions during the mainshock, nine aftershocks are selected to calculate the spectral ratios. The magnitudes of these aftershocks range from 4.0 to 5.0. The initial velocity structure model is taken from the PS-logging data at the KiK-net station.

The right and left panels of Fig. 4.1 show the observed spectral ratios of surface to underground for aftershocks and theoretical spectral ratios calculated with identified velocity structures for horizontal components and those for vertical components, respectively. It can be seen from the right panel of Fig. 4.1 that the peak value at the 0.65 s of theoretical spectral ratio for S-wave and the curve shape fit well with the observed spectral ratios for aftershocks in the horizontal component. It can be also seen from the left panel of Fig. 4.1 that the fitting between theoretical spectral ratio for P-wave and observed spectral ratios in the vertical component is in good agreement, and the peak values at about 0.3 s are almost the same. From the horizontal and vertical spectral ratios, the optimum S- and P-wave velocity structures are obtained. Fig. 4.2 shows the initial and identified S- and P-wave velocity structures between 0.0 m and -100.6 m deep at FKSH11.

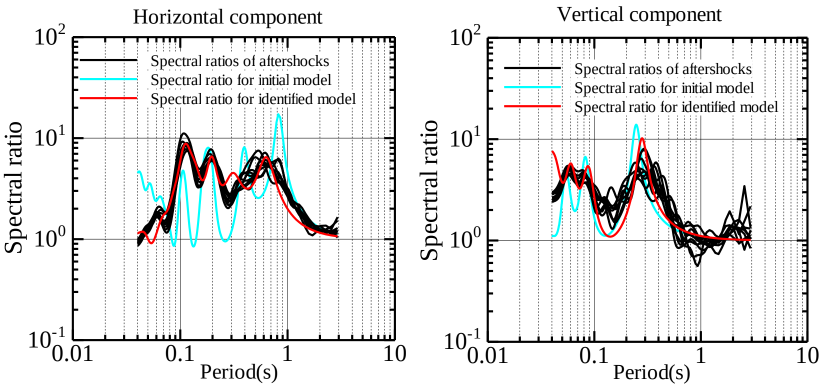

Figure 4.1. The observed spectral ratios of surface to underground (-100.6 m deep) for aftershocks and the theoretical spectral ratios calculated with the initial and identified S- and P-wave velocity structures.

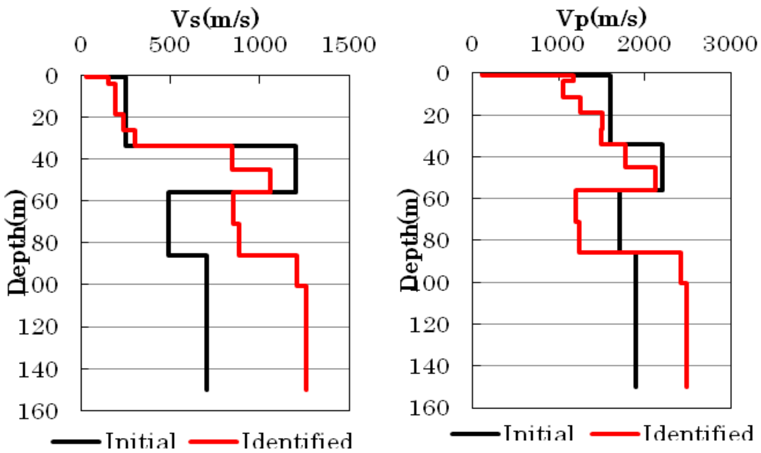

Figure 4.2. The initial and identified S- and P-wave velocity structures at FKSH11.

Fig. 4.3 shows the comparisons of four different spectral ratios: the average H/V spectral ratios of the observed S-wave motions and coda motions for aftershocks, the H/V spectral ratio of microtremors, and the theoretical H/V spectral ratio calculated with the identified S- and P-wave velocity structures between 0.0 m and -100.6 m deep. It can be seen that they fit well with one another, especially for the peak value at about 0.65 s. It suggests that the underground velocity structure can be obtained from the H/V spectral ratio of surface ground motions from aftershocks. Furthermore, it suggests that the underground velocity structure can be identified from H/V spectral ratio of microtremors directly. It follows that the velocity structure can be identified everywhere as long as the microtremor measurement is obtained, even if the strong motion records are not observed.

In order to verify the above supposition, the velocity structure at one damaged site of Yamatouchi in the Yabuki town about 3 km far away from FKSH11 is identified from the H/V spectral ratio of microtremors under the assumption that the velocity structure on the basement of damage site and FKSH11 station is the same. Fig. 4.4 shows the comparison between the H/V spectral ratio of microtremors and the theoretical H/V spectral ratio calculated with the identified velocity structures at the damaged site of Yamatouchi. Fig. 4.5 shows the comparison of the S- and P-wave velocity structures between initial models and identified ones. The good fitting of H/V spectral ratios for the peak values in the 0.04 s-3.0 s period range and the curve shape suggest that the identified velocity structures are also reliable at the damaged site. In other words, the method of identifying velocity structures from the H/V spectral ratio of microtremors is valid and applicable.

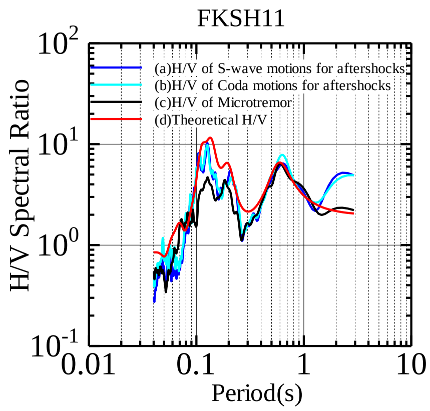

Figure 4.3. The average H/V spectral ratios of S-wave motions (a) and coda motions (b) for aftershocks, the H/V spectral ratio of microtremors (c), and the theoretical H/V spectral ratio (d) calculated with identified S- and P-wave velocity structures at FKSH11.

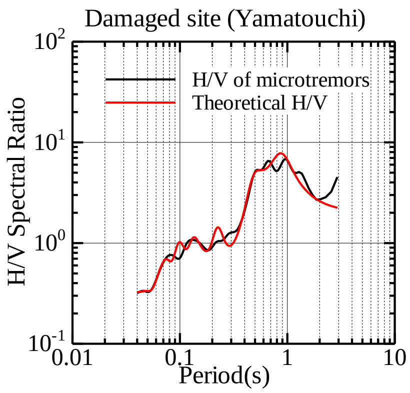

Figure 4.4. The H/V spectral ratio of microtremors and the theoretical H/V spectral ratio calculated with the identified S- and P-wave velocity structures at the damaged site of Yamatouchi, Yabuki town.

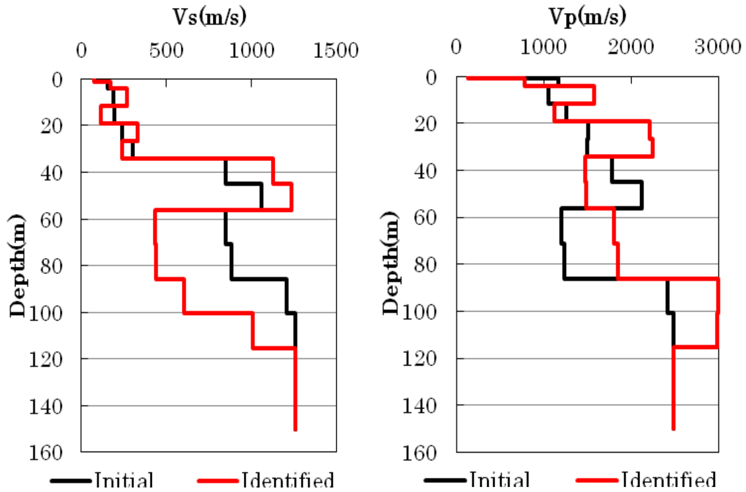

Figure 4.5. The identified S- and P-wave velocity structure at the damaged site of Yamatouchi, Yabuki town, Fukushima Prefecture.

Based on the identified velocity structures and the corresponding transfer functions at FKSH11 and the damaged site of Yamatouchi, the ground motions at the damaged site of Yamatouchi can be estimated according to Eqn. 4.4. The estimated ground motion indices at the damaged site of Yamatouchi are 512 gal for PGA, 79 cm/s for PGV, 6.1 for I_{JMA}, 91 cm/s for SI, respectively. All of these indices are larger than FKSH11. The pseudo-velocity response spectra (pSv) are also compared between the damaged site of Yamatouchi and FKSH11, as is shown in Fig. 4.6. It can be seen that the damaged site has larger pSv of about 400 cm/s around the 1.0 s period relating with the damage of wooden buildings than that of about 200 cm/s at FKSH11. According to the damage data reported by Muraibo et al (2011), the DR is about 70% at the Yamatouchi, while DR is about 47% at the Ippongi where the KiK-net station (FKSH11) is situated. It suggests that the larger DR at the Yamatouchi is due to the larger ground motion indices and the larger pSv. Therefore, the proposition of identifying the velocity structures from the H/V spectral ratio of microtremors is proved to be valid and can be applied to estimate the ground motions at other damaged sites from now on.

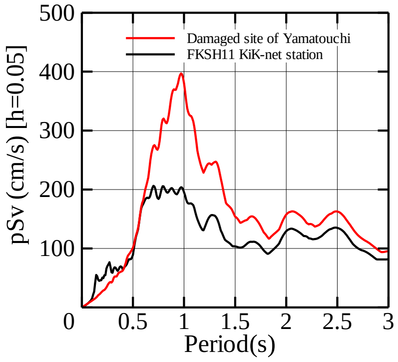

Figure 4.6. The pseudo-velocity response spectra (damping ratio h=0.05) at the damaged site of Yamatouchi and at FKSH11.

5. CONCLUSIONS

The relationship between the DRs and ground motion characteristics in the damaged districts along the Tohoku and Kanto area during the 2011 off the pacific coast of Tohoku earthquake was investigated. A method of estimating the ground motions was proposed using the velocity structures identified from the H/V spectral ratios of microtremors at the damaged sites in order to construct a more accurate fragility curve based on the DRs and ground motion characteristics at the damaged sites. The following conclusions can be concluded:

(1) DRs correlate with ground motion indices, such as PGA, PGV, I_{JMA} and SI. Generally, more DRs, larger ground motion indices. Also, DRs correlate better with velocity indices such as PGV and SI than acceleration ones such as PGA and I_{JMA}.

(2) DRs greater than 30% occur when the PGV is larger than 25 cm/s and PGA is larger than 300 gal, and then the equivalent predominant period ranges from 0.2 s to 1.0 s.

(3) The pseudo-velocity response spectra at the periods less than 0.5 s during this earthquake are quite larger than those during the Kobe earthquake, while those at the periods from 1.0 s and 1.5 s relating with the damage of wooden buildings during this earthquake are smaller than those during the 1995 Kobe earthquake. It may be regarded as the main reason for small DRs.

(4) The consistency of H/V spectral ratios between earthquake and microtremors suggests that the underground velocity structures can be identified by fitting the microtremor H/V spectral ratio with the theoretical one which is calculated as the ratio of transfer function for S-wave motions to that for P-wave motions together with a coefficient as a function of the square root of the P- and S-wave velocity ratio of the bedrock.

(5) The estimated ground motion indices at one damage site of Yamatouchi are larger than those at the KiK-net station (FKSH11). It agrees well with the damage survey that Yamatouchi has a larger DR

than Ippongi where the FKSH11 KiK-net station is situated. This indicates our estimation is reasonable and the method of estimation can be applied at other damaged sites.

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