EFFECTS OF LOCAL SITE AMPLIFICATION ON DAMAGE TO WOODEN HOUSES IN NEAR-SOURCE REGION FOR THE 2007 NOTO HANTO EARTHQUAKE

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Abstract: Effects of local site amplification characteristics on strong ground motions and damage to wooden houses in Hashiride and Kuroshima districts of Monzen area, Wajima city, Japan, during the 2007 Noto Hanto earthquake, are examined based on damage survey and microtremor measurements. Using simplified analytical models of surface soils and wooden houses for the districts, response spectra of strong ground motions and maximum drift angles of wooden houses are simulated. Comparing the simulated results with the observed damage, it is revealed that the wooden-house responses are mainly controlled by strong ground motions with a period of about 1-3 s, at which the site amplification factors were significantly influenced by impedance ratios (V_S contrasts) and nonlinear properties of surface soils in the districts. It is thus indicated that the heavily damage to wooden houses could be due to low ground impedance ratio resulting in strong soil nonlinearity while the slightly ones could be due to high ground impedance ratio inducing weak soil nonlinearity.

1. INTRODUCTION

The Noto Hanto earthquake of March 25, 2007, destroyed over 600 residential buildings at the cities of Wajima and Anamizu in the northwest area of the Noto Peninsula, Ishikawa Prefecture, Japan. Within Hashiride and Kuroshima districts of Monzen area, Wajima city, in particular, a large number of two-storied wooden houses sustained either partial or complete collapse typically of a soft first story (see Photo 1 and Figure 1). To examine causes of the building damage during the 2007 earthquake, the effects of surface soil conditions on strong ground motion characteristics and wooden-house responses should be properly estimated in the districts.

The objective of this article is to evaluate the maximum drift angles of wooden houses considering local site effects in Hashiride and Kuroshima districts during the 2007 Noto Hanto earthquake based on dynamic response analyses of simplified single-degree-of-freedom (SDOF) building systems and surface soil models, which are resulted from inventory survey of building damage and microtremor measurements in the districts.

2. DAMAGE SURVEY OF WOODEN HOUSES IN HASHIRIDE AND KUROSHIMA

An inventory survey was conducted for all buildings in the central zones of Hashiride and Kuroshima districts. The survey zones are shown in Figure 1 as broken thick lines. These zones are hereinafter labeled as Aa-Ae in Hashiride and Ba-Bc, Ca-Cc, and Da-Dd in the northern, middle, and

Photo 1. Examples of damage to wooden houses in (a), (b) Hashiride and (c) Anamizu during main shock.

southern Kuroshima districts, respectively. Location, age, use, structural material and system, number of stories, and foundation of each building were investigated as well as observed damage level, which is classified into three grades: D0 (no damage), D1-D3 (slightly and moderately damaged), and D4-D5 (heavily damaged and collapsed including demolished) according to the studies by Okada and Takai (1999). Number of buildings investigated was totally 482 in the target zones, and all of them were one- or two-storied wooden houses which are traditional in the Noto Peninsula.

Figure 2 indicates the distribution of damage ratios for wooden houses investigated at zones Aa-Ae, Ba-Bc, Ca-Cc, and Da-Dd in Hashiride and Kuroshima districts. In Hashiride, the values of D4-D5 ratios are about 0.1-0.2 through zones Aa-Ae. In Kuroshima, however, the damage ratios of wooden houses at the northern and mid zones Ba-Bc and Ca-Cc are larger than those at the southern zone Da-Dd. In zones Ba-Bc and Ca-Cc, furthermore, the damage ratio varies at a maximum of about 0.3 depending on distance from the seashore, which is running in the

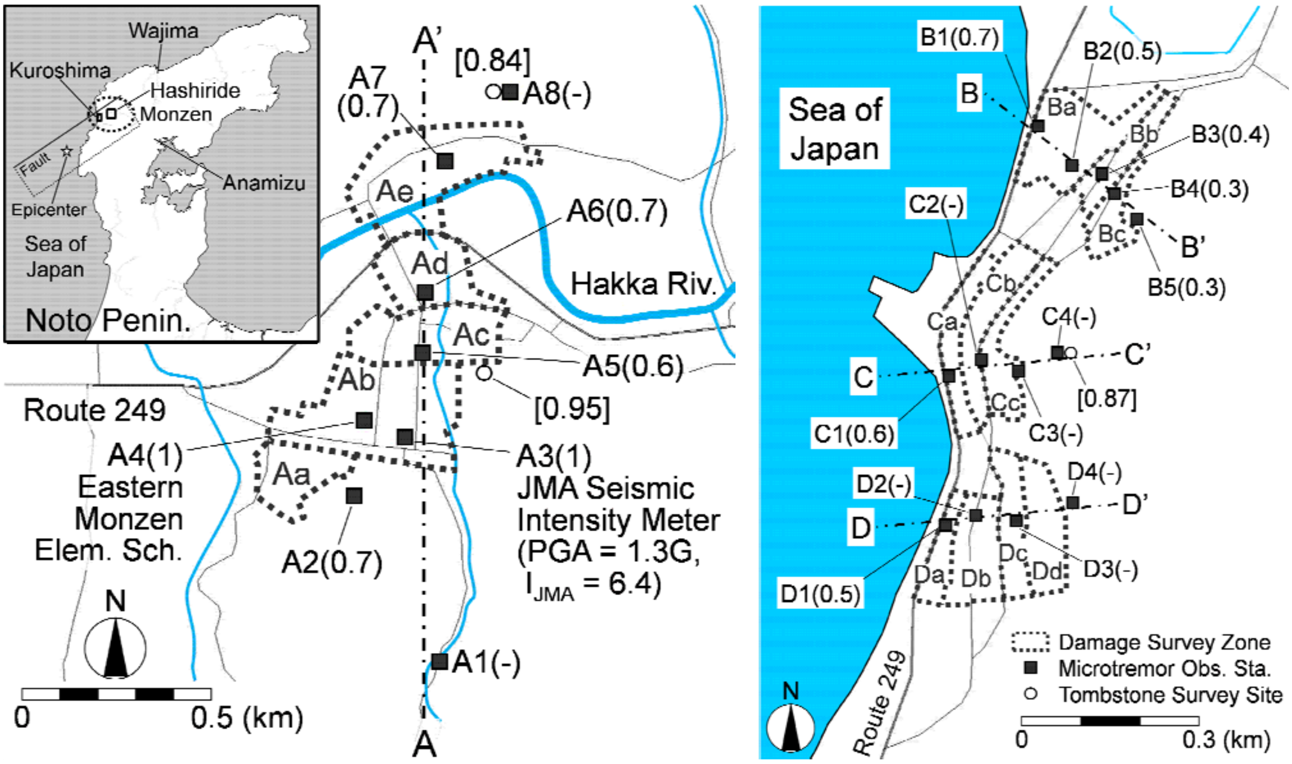

Figure 1. Maps showing zones for building inventory survey, locations of microtremor observation stations, and tombstone investigation sites in Hashiride (left) and Kuroshima (right). Values within ( ) and [ ] in the figure indicate H/V peak periods (in s) of microtremors and overturning ratios of tombstones, respectively. (-) means that microtremor H/V have no significant peak at the station.

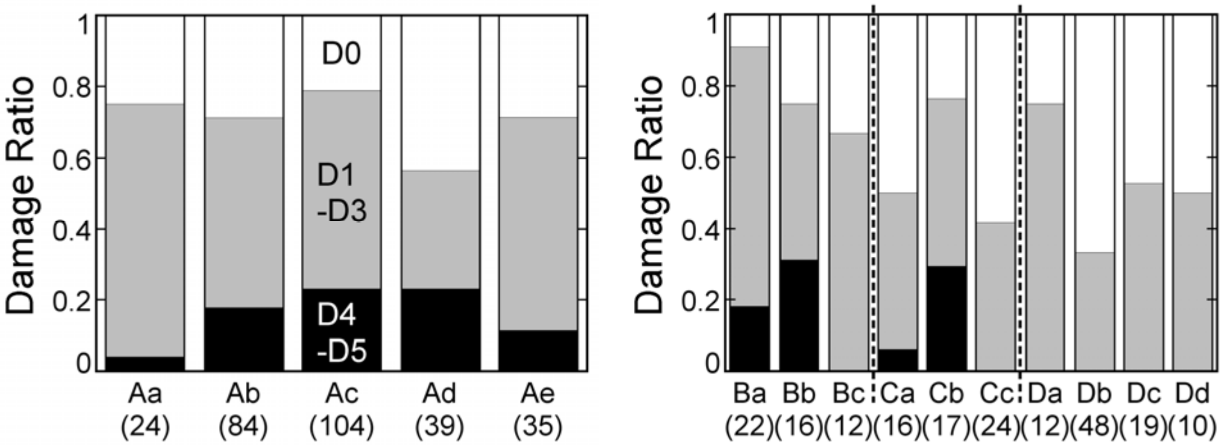

Figure 2. Distribution of damage ratios for wooden houses investigated at zones Aa-Ae in Hashiride (left) and Ba-Bc, Ca-Cc, and Da-Dd in Kuroshima (right). Numbers within ( ) in the figure express those of buildings surveyed.

north-south direction at the western side of Kuroshima. These indicate that the damage ratio of wooden houses within Kuroshima district changes drastically in both the north-south and east-west directions.

3. S-WAVE VELOCITY PROFILING OF SURFACE SOILS IN HASHIRIDE AND KUROSHIMA

To determine S-wave velocity (V_S) structures of surface soils for estimating local site effects in Hashiride and Kuroshima, single-station measurements of microtremors using a three-component sensor were performed at 21 sites shown in Figure 1 as solid squares. These observation stations are hereinafter called as A1-A8 in Hashiride and B1-B5, C1-C4, and D1-D4 in the northern, mid, and southern Kuroshima districts, respectively. In Hashiride, stations A2-A7 are located on an alluvial plain while stations A1 and A8 are on the southern and northern hills, where the building damage was slight.

Open circles in Figure 3 show horizontal-to-vertical (H/V) spectra of microtremors (Nakamura, 1989) observed at stations A1, A4, A6, A7, B1, B3, B5, C2, D1, and D3. At stations A1 located on the southern hill in Hashiride and C2, D1, and D3 in the mid and southern Kuroshima, the observed H/V spectra have no significant peaks. This suggests that the engineering bedrock outcrops at these stations. At stations A4, A6, and A7 located on the plain in Hashiride and B1, B3, and B5 in the northern Kuroshima, on the other hand, the observed H/V spectra have significant peaks. The H/V peak period varies in the ranges of 0.5-1 and 0.3-0.7 s in Hashiride and the north Kuroshima, respectively. The variation of H/V spectra suggests that the V_S profiles change drastically along the lines passing through stations A1-A8 in Hashiride and B1-B5 in the northern Kuroshima.

The inverse analyses of microtremor H/V spectra (Arai and Tokimatsu, 2004, 2005) are performed to determine the V_S structures for the 21 observation stations. In the inversion, the following assumptions are made: (1) the soil profile down to engineering bedrock at each station consists of a two-layered half-space, and (2) the V_S values of top and base layers (sediments and bedrock) at each station are assigned to those listed in Table 1, which are based on a borehole data at the eastern Monzen elementary school (station A4) in Hashiride, available geological information in the district (Monzen Town, Ishikawa Prefecture, 1970), and the spatial variation of H/V shapes observed in Kuroshima. This leaves only the thickness of sediments unknown in the inversion.

Table 1. Two-layered analytical models of surface soils inferred in Hashiride and Kuroshima.

District	Soil Type	Sediment V_S (m/s) [1.8]	Bedrock V_S (m/s) [2.0]	Natural Site Period, T_0 (s)
Hashiride	Clayey	145	520	0.5, 0.7, 1
Northern Kuroshima	Sandy	145	380	0.3, 0.5, 0.7
Mid Kuroshima		215	380	0.3, 0.5
Southern Kuroshima		275	400	0, 0.3, 0.5

Values within [ ] in the table denote assumed densities (in Mg/m^3).

Figure 4 shows two-dimensional (2-D) V_S structures thus determined for lines A1-A8 in Hashiride and B1-B5, C1-C4, and D1-D4 in the northern, mid, and southern Kuroshima districts, respectively. Broken lines in Figure 3 are the H/V spectra of surface waves for the inverted V_S profiles. Good agreements between the observed and theoretical H/V spectra indicate that the inverted structures are reasonably reliable. In Figure 4, within Hashiride, it is estimated that the clayey sediments with a depth of about

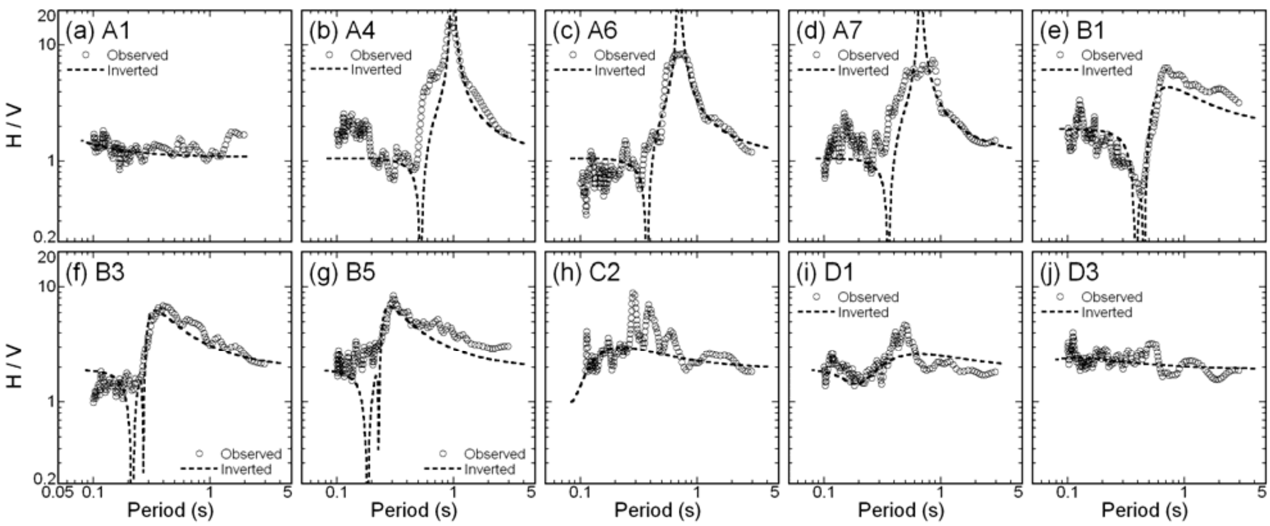

Figure 3. H/V spectra of microtremors (open circles) compared with those of surface waves (broken lines) for soil profiles inferred by H/V inversion at stations A1, A4, A6, and A7 in Hashiride, B1, B3, and B5 in northern Kuroshima, C2 in mid Kuroshima, and D1 and D3in southern Kuroshima.

20-40 m overlie the engineering bedrock in the plain while the bedrock outcrops on the northern and southern hills. In Kuroshima, on the other hand, the engineering bedrock is covered by sandy soils with a depth of about 10-25 m and slopes gradually seaward. Also indicated in the figure is that the impedance ratios between sediments and bedrock in Hashiride and the northern Kuroshima are about 0.3 or lower while those in the mid and southern Kuroshima are about 0.5 or higher. The spatial variation of ground impedance ratios is consonant with that of wooden-house damage ratios shown in Figure 2, suggesting that the impedance ratios of surface soils could have significant effect on the damage to wooden houses.

4. SIMULATION OF GROUND AND BUILDING RESPONSES IN HASHIRIDE AND KUROSHIMA

4.1 Outline of Method and Condition for Simulation

To estimate local site amplifications and wooden-house drift angles in Hashiride and Kuroshima during the main shock, a simplified analytical method proposed by Morii and Hayashi (2003) is employed in this study. In the simplified method, one-dimensional (1-D) nonlinear site amplification is approximately computed by using a response spectrum technique for two-layered ground model, and the maximum drift angle of wooden house is roughly calculated by using the equivalent-performance response spectrum of a SDOF building system (Hayashi, 2002). Details of the response analyses used are found in the studies by Hayashi (2002), Morii and Hayashi (2003), and Hayashi *et al.* (2007).

In the site amplification analyses, two-layered surface soil models listed in Table 1 are used for Hashiride and the northern, mid, and southern Kuroshima districts. In that table, natural site periods, T_0, are parametrically set, based on the V_S profiles estimated from microtremors in the districts (Figure 4), and the stress-strain relationships for clayey and sandy soils are inferred from the studies by Sun *et al.* (1988) and Kokusho (1980), respectively. Also required in the analyses is the acceleration response spectrum with a damping ratio of 0.05 for input bedrock motion, S_{aB}, which can be characterized by its predominant period, T_P, and maximum velocity, V_{max} (Architectural Institute of Japan, 1997). In this study, T_P and V_{max} of the bedrock motion are assigned as 1 s and 80 cm/s, respectively, based on the following two facts:

(1) T_P of strong ground motion records during the main shock, which were provided by K-NET and KiK-net observation systems of the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan and the Japan Meteorological Agency (JMA), could be less than about 1 s at the observation stations with fault distance under about 100 km (Figure 5).

(2) The overturning ratios of tombstones observed at several sites in the districts were over about 0.8 (see Figure 1), suggesting that V_{max} could be larger than 80 cm/s when T_P is less than about 1 s (Kaneko and Hayashi, 2000).

In the building response analyses, the bi-linear model is used for the force-displacement relationship of SDOF system, and its dynamic properties are inferred from the results of inventory survey for wooden houses in Hashiride and Kuroshima and detailed ones in other districts in Japan (e.g., Shimizu *et al.*, 2005). The equivalent height and yield drift angle of SDOF system are predetermined as 4.5 m and 1/100, respectively. The yield base shear coefficient of the system, C_y, is parametrically set as 0.2, 0.4, and 0.6.

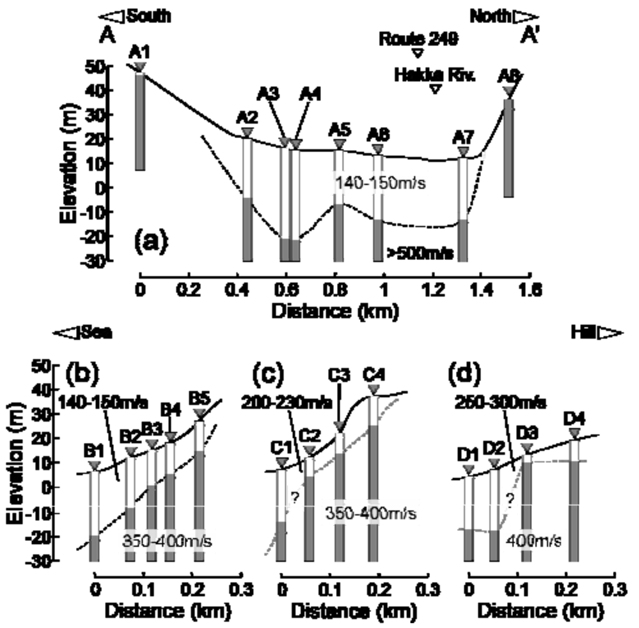

Figure 4. S-wave velocity structures estimated from microtremors in (a) Hashiride, (b) northern Kuroshima, (c) mid Kuroshima, and (d) southern Kuroshima.

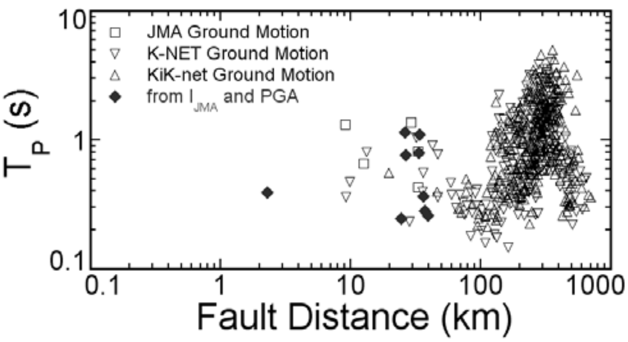

Figure 5. Relationship between predominant periods, T_P, of strong ground motion records and fault distances of observation stations during main shock.

4.2 Drift Angle and Damage Ratio of Wooden Houses

Solid, broken, and chained thick lines in Figure 6 indicate the acceleration response spectra of ground surface motions, S_{aS}, estimated from the site amplification analyses for each natural period T_0 set in Hashiride and the northern, mid, and southern Kuroshima districts. Chained thin lines in the figure are the acceleration response spectrum of the input bedrock motion, S_{aB}, inferred in the analyses. Also shown in

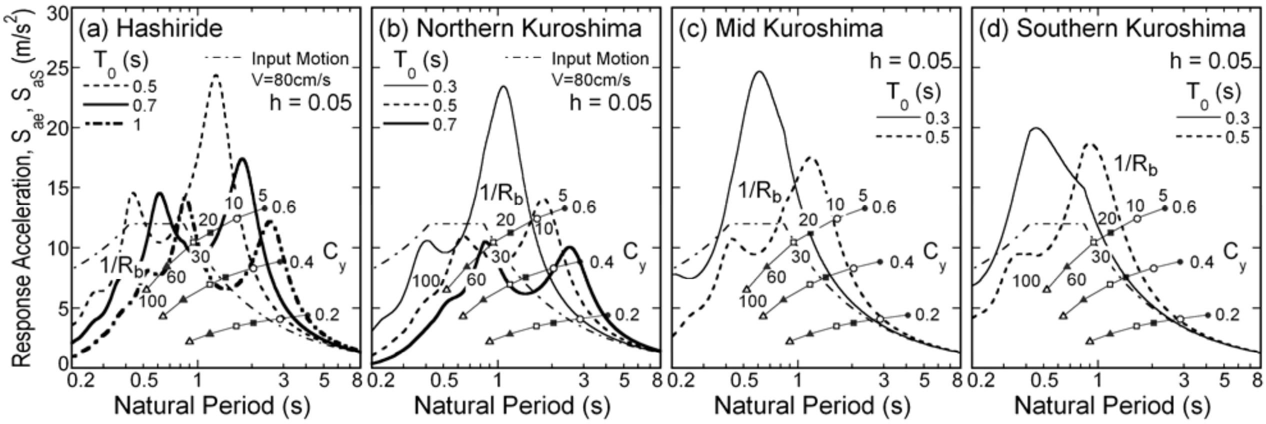

Figure 6. Comparison between equivalent-performance response spectra for wooden houses, S_{ae}, and acceleration response spectra of strong ground motions, S_{aS}, estimated in (a) Hashiride, (b) northern Kuroshima, (c) mid Kuroshima, and (d) southern Kuroshima.

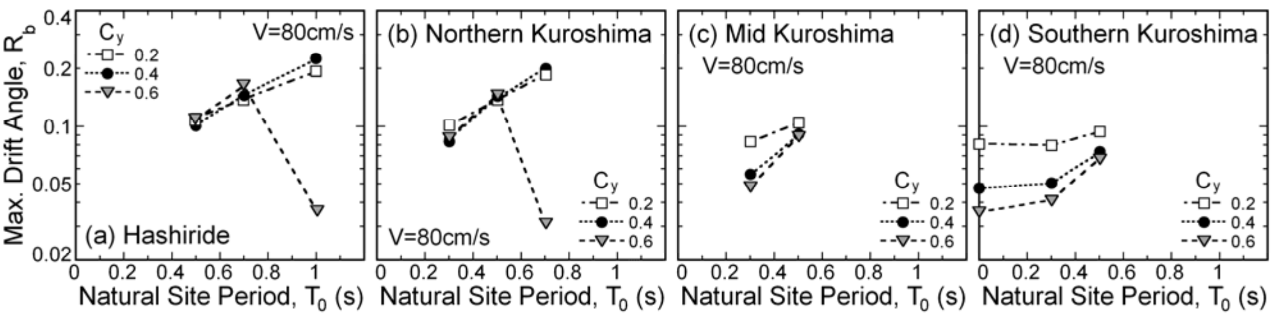

Figure 7. Variation of wooden-house drift angle R_b estimated for each yield base shear coefficient C_y with natural site period T_0 in (a) Hashiride, (b) northern Kuroshima, (c) mid Kuroshima, and (d) southern Kuroshima.

the figure as symbolized thin lines are the equivalent-performance response spectra of wooden houses, S_{ae}, derived from the building analyses for each yield base shear coefficient C_y. In Figure 6, the maximum drift angle, R_b, of a wooden house for C_y at a site with natural period T_0 can be determined from a crossing point between the response spectra S_{ae} and S_{aS} corresponding to C_y and T_0, respectively (Hayashi, 2002; Hayashi *et al.*, 2007). Figure 7 summarizes the variation of the wooden-house drift angle R_b evaluated for each yield base shear coefficient C_y with natural site period T_0 in the districts.

From Figure 7, the maximum drift angles R_b of wooden houses for C_y = 0.2 and 0.4 are over about 1/10 in Hashiride and the northern Kuroshima districts, where building damage was significant. In the other districts of Kuroshima, however, the values of R_b decrease southward and are less than about 1/15 in the southern Kuroshima, where the building damage was slight. Comparing Figures 4, 6, and 7, it is revealed that the maximum drift angles of wooden houses (R_b) could mainly be controlled by the response spectra of strong ground motions (S_{aS}) at a period of about 1-3 s. In Kuroshima, also indicated is that the strong ground motion with such a period is significantly amplified at the northern (heavily damaged) district due to low ground

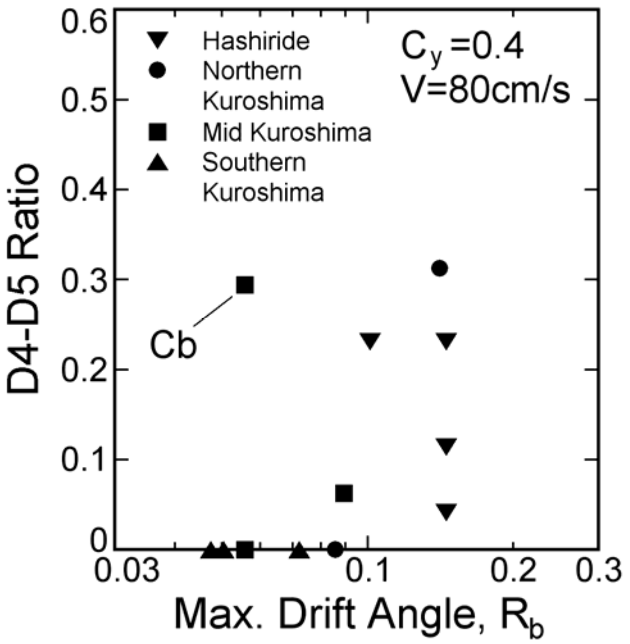

Figure 8. Relationship between estimated drift angles R_b of wooden houses with C_y = 0.4 and observed D4-D5 ratios in Hashiride and Kuroshima.

impedance ratio resulting in strong soil nonlinearity while it is not at the southern (slightly damaged) district due to high ground impedance ratio leading to weak soil nonlinearity.

Furthermore indicated from Figure 7 is that the maximum drift angles R_b of wooden houses for $C_y = 0.2$ and 0.4 increase with lengthening the natural site period T_0 in any district. In case of wooden house for $C_y = 0.6$, however, the values of R_b reduce drastically at sites with $T_0 = 1$ s in Hashiride and $T_0 = 0.7$ s in the northern Kuroshima. Based on Figures 6 and 7, it is considered that the R_b reduction in the districts are chiefly caused by increasing soil damping with lengthening T_0, and thus, the response spectra S_{aS} of ground motions at sites with large T_0 values could get smaller than the equivalent-performance response spectra S_{ae} of wooden houses with high C_y values.

Figure 8 shows the relationship between the evaluated drift angles R_b of wooden houses with $C_y = 0.4$ and the observed D4-D5 ratios in Hashiride and Kuroshima districts. In the figure, the R_b data estimated at sites with $T_0 = 1$ s in Hashiride and $T_0 = 0.7$s in the northern Kuroshima are not involved because of the consideration stated previously. The figure suggests that the maximum drift angles R_b of wooden houses could be over 1/10 at sites where the D4-D5 ratios exceed about 0.1. Similar trends exist in cases of $C_y = 0.2$ and 0.6. These also indicate that the simulated drift angles R_b are reasonably reliable.

5. CONCLUSIONS

Effects of local site amplification characteristics on strong ground motions and damage to wooden houses in Hashiride and Kuroshima districts of Monzen area, Wajima city, Japan, during the 2007 Noto Hanto earthquake, are examined based on building inventory survey and microtremor single-station measurements. Using simplified analytical models of surface soils and wooden houses for the districts, response spectra of strong ground motions and maximum drift angles of wooden houses are simulated. Comparing the simulation results with the observed damage, the following conclusions are made:

1. The wooden-house responses during large earthquakes are mainly controlled by strong ground motions with a period of about 1-3 s.
2. The site amplification factors at a period of about 1-3 s were significantly influenced by impedance ratios (V_S contrasts) and nonlinear properties of surface soils in the districts.
3. The heavily damage to wooden houses could be due to low ground impedance ratio leading into strong soil non-linearity while the slightly ones could be due to high ground impedance ratio inducing weak soil nonlinearity.

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