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LETTER

Observation of earthquake ground motion due to aftershocks of the 2016 Kumamoto earthquake in damaged areas

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Abstract

We have conducted observation of earthquake ground motion due to aftershocks of the 2016 Kumamoto earthquake at 26 temporary stations in damaged areas of Kumamoto city, Mashiki town, Nishihara village and Minami-Aso village (partly in Aso city) in Kumamoto prefecture, Japan. Continuous recordings of ground acceleration were acquired in a period of about 1 month after the occurrence of the main shock on April 16, 2016. This preliminary analysis of the observed records clearly indicates strong effects of local geological condition in the heavily damaged districts in Mashiki town and Nishihara village. Spectral ratios of the ground motions at the stations in the severely damaged districts to those at the reference sites are characterized by large amplitudes at periods of 0.5–1 s. Peak ground velocities and seismic intensities are also large at the sites. Seismic intensities at the stations in the damaged districts are larger by an intensity of one at the maximum than those at the stations with the minor damage. The ground motions at the stations in Kumamoto city are rich in later phases with long duration suggesting basin effects. However, site amplification effects could not clearly be identified at the stations in the Minami-Aso area from the results in the conventional spectral ratio approach.

Keywords: The 2016 Kumamoto earthquake, Aftershock, Earthquake ground motion, Strong motion observation, Site amplification

Introduction

Heavy damage was experienced in Kumamoto prefecture, Japan, during the 2016 Kumamoto earthquake with an M_J of 7.3 on April 16, 2016 (main shock in the following), and its foreshock with an M_J of 6.4 on April 14, 2016. The hypocenter of the foreshock was determined to be beneath the northeastern part of the Hinagu fault zone, while the main shock occurred along the Futagawa–Hinagu fault zone (e.g., Asano and Iwata 2016; Shimizu et al. 2016). The damaged areas spread widely near the fault zones from Kumamoto city to Minami-Aso village in Kumamoto prefecture. In particular, the heavy damage was concentrated in the focal area in Mashiki town in Kumamoto prefecture. During the foreshock and the main shock, strong motion records were obtained by seismic intensity meters installed in the damaged areas, and a strong motion sensor at KiK-net Mashiki (KMMH16). Preliminary analysis of these data indicated that the ground motions are extremely large in the damaged areas (e.g., Miyake et al. 2016). For example, peak acceleration of strong motion records observed at the strong motion site in Mashiki town is approximately 0.9 g (JMA 2016). Si et al. (2016) compared these peak values with those expected from existing attenuation equations and indicated that some of observed values near the focal area are larger than the expected ones. Understanding of physical and engineering characteristics of these strong motion records is important for reasons on the heavy damage experienced during the earthquakes. However, existing ground motion data are not enough to know spatial variation of ground motion characteristics in the wide damaged area. Actually the building damage was not uniform even in Mashiki town (e.g., Yamada et al. 2016).

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Furthermore, the affected areas exhibit a wide variety of soil conditions, which may be significantly different from Kumamoto city in the Kumamoto plain to mountain area around Aso volcano (see Fig. 1). Previous researches on strong ground motion of shallow crustal earthquakes, such as the 1995 Kobe earthquake, indicated the important effects of subsurface structure as well as source rupture effects (e.g., Kawase 1996). Therefore, geological differences in the damaged areas have to be considered in the understanding of the characteristics of the strong shaking during the earthquakes. However, the site effects in the areas are not well known in previous studies.

In this study, we have conducted an observation of earthquake ground motions due to aftershocks of the 2016 Kumamoto earthquake at 26 stations in the damaged areas of Mashiki town, Nishihara village, Minami-Aso village (including partly Aso city) and Kumamoto city to investigate the ground vibration characteristics in the areas.

Measurements

The observation of ground motion due to aftershocks was mainly conducted from the 16 April to the 22 May at the 26 temporary stations in Kumamoto prefecture, Japan. Since the installation was started in the morning of the 16 April, ground motion of the main shock was not recorded at our stations. The locations of the stations are shown in Fig. 1 and also listed in Table 1 with geological classification (Editorial Meeting of Geologic Map of Kumamoto 2008), damage of mainly wooden houses near the stations. The table also contains epicentral distances for the main shock. Figure 1b, c indicates detailed locations of the stations in Mashiki town and Nishihara village with topographic maps by Geographical Information Authority of Japan. MK01 in Fig. 1b is located near a main governmental office of Mashiki town, where strong motion records of the main shock were obtained by a seismic intensity meter. The distance between our station and the intensity meter is about 30 meters. MK02 is also situated on the surface very close to a strong motion station of the KiK-net in Mashiki town. The other stations from MK03 to MK13 are located on the ground surface in Mashiki town with various damages as given in Table 1. Heavy building damage especially in wooden houses was experienced around MK01, 03, 05, 07 and

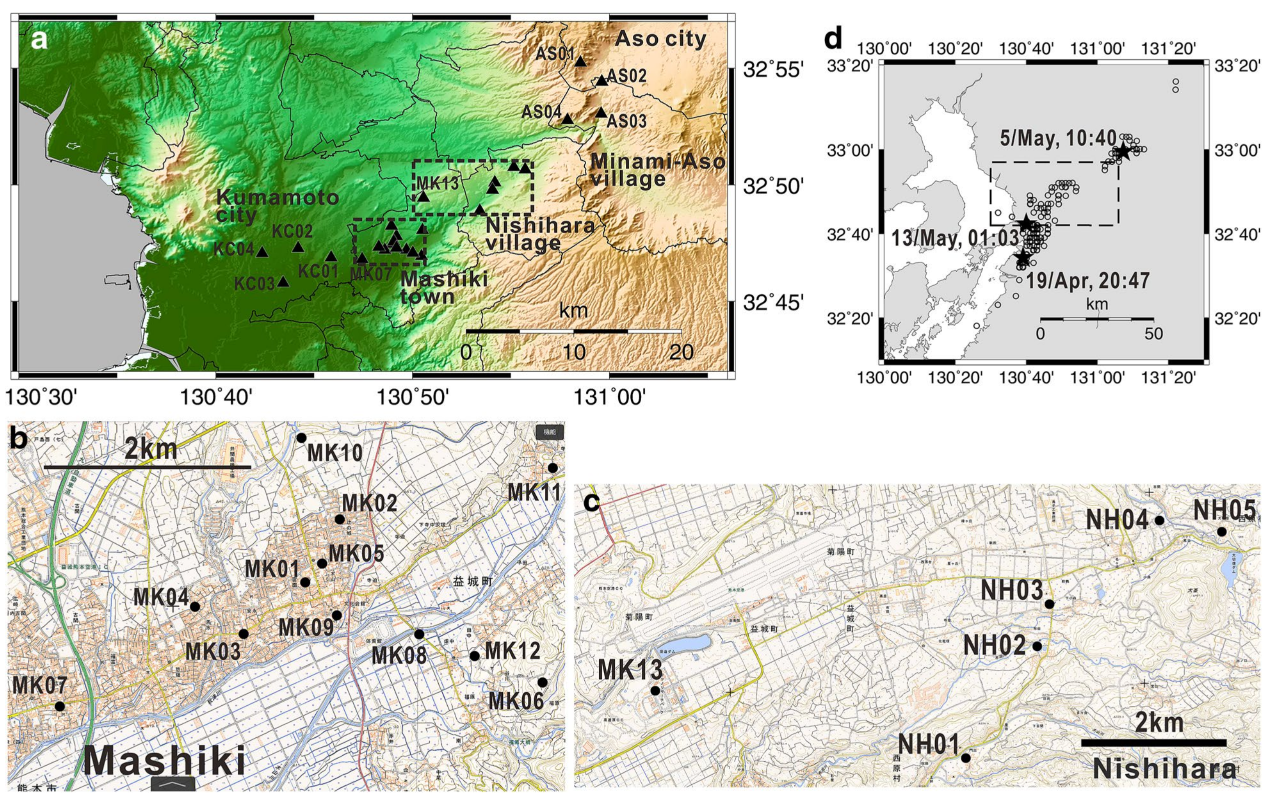

Fig. 1 Locations of stations in **a** whole area, **b** Mashiki town, **c** Nishihara village, and **d** epicenters of the events (*circles* and *stars*) used in this study. *Stars* show epicenters for events whose records are displayed in Figs. 3, 6, 9 and 12 as examples. It is noted that *MK06*, *NH01* and *AS01* are used as reference sites in Mashiki town, Nishihara village and Minami-Aso area, respectively. *Broken squares* in **a** show areas in **b** and **c**, while *broken square* in **d** corresponds to map of **a**

Table 1 List of stations with surface geology, damage and epicentral distance for main shock

Region	District	Code	Lat.	Long.	Start	End	Geology	Damage	Epi. dist (km)
Aso and Minami-Aso	Kurumagaeri	AS01	32.920410	130.975480	2016/04/23 11 A.M.	2016/05/11 11 A.M.	Pyroxene andesite	Slight	27.3
	Shimono	AS02	32.906830	130.993700	2016/04/23 02 P.M.	2016/05/12 01 P.M.	Holocene fan sediment	Slight	27.6
	Kawayou	AS03	32.884100	130.992940	2016/05/02 06 P.M.	2016/05/22 09 A.M.	Rhyolitic lava	Heavy	26.1
	Tateno	AS04	32.879480	130.964540	2016/05/03 01 P.M.	2016/05/16 07 P.M.	Talus sediment	Moderate	23.6
Kumamoto city	Higashimachi, Higashi-ku	KC01	32.781222	130.764500	2016/04/20 10 A.M.	2016/04/30 08 P.M.	Pleistocene middle terrace sediment	Moderate	3.1
	Suizenji, Chuo-ku	KC02	32.787970	130.736510	2016/04/16 05 P.M.	2016/05/20 04 P.M.	Pleistocene lower terrace sediment	Slight	4.5
	Tainoshima, Minami-ku	KC03	32.763166	130.723796	2016/05/02 09 A.M.	2016/05/16 07 A.M.	Alluvium	Slight	3.7
	Kotohira, Chuo-ku	KC04	32.784400	130.706020	2016/04/22 11 A.M.	2016/05/01 01 P.M.	Alluvium	Slight	6.2
Mashiki	Miyazono	MK01	32.791222	130.816194	2016/04/16 11 A.M.	2016/05/21 08 A.M.	Early Pleistocene pyroclastic sediments	Heavy	6.6
	Tsujinoshiro	MK02	32.796639	130.819806	2016/04/16 12 A.M.	2016/05/01 05 P.M.	Early Pleistocene pyroclastic sediments	Slight	7.3
	Yasunaga	MK03	32.786750	130.809833	2016/04/16 02 P.M.	2016/05/01 04 P.M.	Pleistocene lower terrace sediment	Heavy	5.8
	Mamizu	MK04	32.789056	130.804778	2016/04/16 03 P.M.	2016/04/30 02 P.M.	Pleistocene volcanic sediments	Slight	5.7
	Miyazono	MK05	32.792750	130.817639	2016/04/16 04 P.M.	2016/05/01 07 A.M.	Early Pleistocene pyroclastic sediments	Heavy	6.8
	Fukuhara	MK06	32.782306	130.841056	2016/04/16 05 P.M.	2016/05/16 00 P.M.	Crystalline schist	Slight	8.1
	Hirosaki	MK07	32.780250	130.790667	2016/04/16 06 P.M.	2016/04/30 03 P.M.	Pleistocene middle terrace sediment	Heavy	4.0
	Fukuhara	MK08	32.786722	130.828361	2016/04/19 10 A.M.	2016/04/30 01 P.M.	Alluvium	N/A	7.2
	Terasako	MK09	32.788194	130.819722	2016/04/19 11 A.M.	2016/04/30 04 P.M.	Pleistocene lower terrace sediment	Heavy	6.7
	Miyazono	MK10	32.804000	130.815611	2016/04/19 01 P.M.	2016/04/30 10 A.M.	Early Pleistocene pyroclastic sediments	N/A	7.6
	Jicyu	MK11	32.800833	130.841833	2016/04/19 03 P.M.	2016/04/30 12 A.M.	Early Pleistocene pyroclastic sediments	Slight	9.2
	Fukuhara	MK12	32.784667	130.833667	2016/04/19 05 P.M.	2016/05/16 07 P.M.	Alluvium	Slight	7.6
	Tabaru	MK13	32.823891	130.842807	2016/04/18 01 P.M.	2016/06/22 10 A.M.	Hornblende andesite	Moderate	10.9

Table 1 continued

Region	District	Code	Lat.	Long.	Start	End	Geology	Damage	Epi. dist (km)
Nishihara	Kawahara	NH01	32.814820	130.890180	2016/05/02 02 P.M.	2016/05/22 04 P.M.	Late Pleistocene pyroclastic sediments	Slight	13.8
	Futa	NH02	32.829620	130.901050	2016/05/03 09 A.M.	2016/05/18 10 A.M.	Hornblende andesite	Moderate	15.6
	Komori	NH03	32.834950	130.903080	2016/05/02 01 P.M.	2016/05/22 05 P.M.	Hornblende andesite	Moderate	16.0
	Koga	NH04	32.846089	130.918586	2016/04/18 03 P.M.	2016/06/22 09 A.M.	Talus sediment	Heavy	17.9
	Okirihata	NH05	32.844250	130.928800	2016/05/03 11 A.M.	2016/05/18 22 P.M.	Late Pleistocene pyroclastic sediments	Heavy	18.6

09. In particular, extremely severe damage was observed near MK09 in Terasako district near Akitsu River. MK08 is located in about 100 meters in the west from the Futagawa fault trace (Research Group for Active Faults of Japan 1991). MK06 belongs to a hilly area in the south, where surface geology is classified as crystalline schist (Editorial Meeting of Geologic Map of Kumamoto 2008). This station is regarded as a reference site to estimate site amplification in Mashiki town as explained later.

In the east of Mashiki town, nine stations were established; five stations denoted as NH01–NH05 in Nishihara village and four stations named as AS01–04 in Aso city and Minami-Aso village. Heavy damage was observed around NH04 in Koga district and NH05 in Okirihata district. It is noted that NH03 is located at the same position of the seismic intensity meter in a main governmental office of Nishihara village. NH01 is used as a reference site in the later analysis on site amplification in the area. Three and one stations were established in Minami-Aso village and Aso city, respectively. In the followings, we call this area Minami-Aso area. Heavy damage of buildings was observed around AS03 belonging geologically to alluvium formation. AS01 is installed in a quarry mine and is regarded as a reference site in the area.

We also established four stations in the eastern part of Kumamoto city to know spatial variation of ground motion in the west–east direction of the Kumamoto plain. The area is slightly far from the causative fault. However, moderate-to-slight building damage was observed near KC01 covered with terrace deposits. KC03 and KC04 are located on Quaternary layers of the Kumamoto plain. No major structural damage was seen near the two stations.

A three-component seismometer (JEP6A3 by Mitutoyo) and a recorder (LS7000XT or LS8800 by Hakusan Corp.) were temporarily installed on the surface at each station to obtain continuous records of ground acceleration. The seismometers used are of the same type as Kudo et al. (2002). Internal clock signal of each instrument was calibrated with GPS timing signal every 1–4 h. The observation was mainly started on the April 16 and terminated on the May 22, 2016. It is noted that the observational periods are not synchronized at all the stations as given in Table 1. After records at some of the stations in Mashiki town have been accumulated, the instruments were removed and redeployed in Minami-Aso area or Nishihara village in the first week of May 2016.

In this study, we focused on ground motion records from aftershocks in which the maximum observed intensity was more than 3.0 in the JMA scale. Figure 2a shows a relation between magnitudes and depth of the events. Figure 2b displays a relation between epicentral distance and peak values of ground accelerations for the records at MK01 and NH03 as examples. Since most of the PGAs are smaller than 100 cm/s/s, we neglect nonlinear behavior of soil in this analysis. Figure 1d displays the locations of the epicenters of the events used in the analysis. The hypocenters used for the figure were determined by JMA.

Results in Mashiki town

An example of the observed records in Mashiki town is shown in Fig. 3. Each trace in Fig. 3a indicates ground acceleration observed during an event on the 19 April with a depth of 11 km and an M_J of 5.0. The amplitudes of the ground motion records at MK01, 03, 05, 07 and 09 are large with long duration. In particular, a large initial S-wave motion was observed at MK09. These stations are located in the heavily damaged area of Mashiki town as given in Table 1. On the other hand, the ground

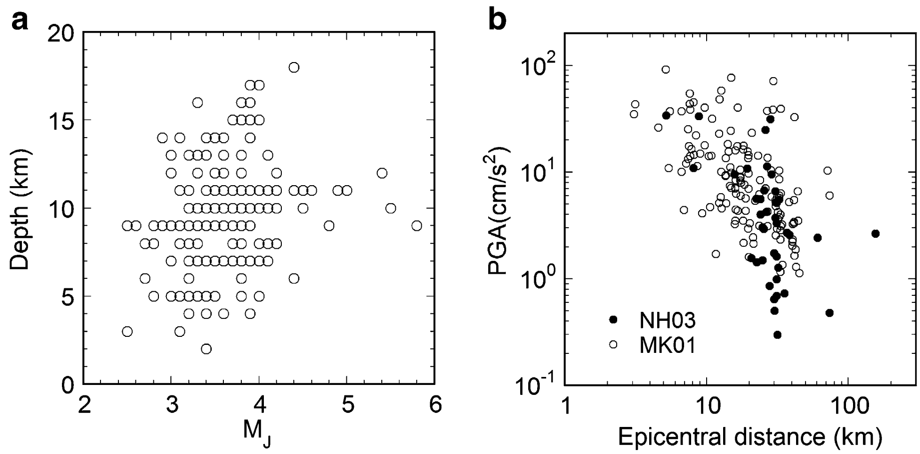

Fig. 2 Characteristics for events and records used in this study. **a** Relation between magnitudes and depths of aftershocks and **b** observed PGAs and epicentral distances at MK01 and NH03

motions at MK06 and 11 are very small in amplitudes. Peak ground acceleration (PGA) and peak ground velocity (PGV) were estimated to compare their ratios with respect to those at the reference station of MK06. The ratios shown in Fig. 4 are averaged ones for all the available records from approximately 140 events. We also calculated differences between the seismic intensities at each site and those at the reference site of MK06 for each event and averaged them. It is noted that the estimated standard deviations for these ratios (PGAs and PGVs) and differences are 0.052, 0.047 and 0.021 on average and sufficiently small, although these are not shown in the figures. The ratios of the peak values and the intensity differences at MK01, 03, 05, 07 and 09 are larger than the other stations. This quantitatively corresponds to the damage degrees around the stations.

We next estimated spectral ratios of all the stations to those at the reference station. Fourier spectra of two horizontal motions were calculated using the acceleration records with a duration of 81.92 s including S-wave portion. The spectra were smoothed with a Parzen windows of 0.1 Hz, and their geometric average was used for individual ratio. Then, the spectral ratios from all the events were averaged. The ratios in Fig. 5 indicate that the dominant peaks can be identified for periods of 0.3–0.5 s at the stations with the large amplitudes. In particular, it is found that the large spectral ratios around a frequency of 0.4 s can be identified as common features in the ratios at MK01, 03, 05 and 09 with the heavy damage. On the other hand, the ratios at MK04, 11 and 12 are small and flat in a frequency range of 0.2–2 s, suggesting minor the site amplification effects. According to Sakai and Nakamura (2004), the low amplitudes of the 1 s motion may be related to the slight damage observed at these stations. It is also noted that a peak at a period of 3 s can be seen at most of the stations in Mashiki town. The stations in the southern part of the area do not have dominant peaks in the long-period range, such as MK08, 11 and 12. These differences may suggest variation of deep subsurface structure near the fault. The integrated ground velocities filtered at periods from 0.05 to 10 s are shown in Fig. 3b. Note that the distance in the figure was measured from the Futagawa fault identified at a location between MK12 and MK06 in the area. This plot suggests that the later phases have a lower apparent velocity than that of initial S-wave, suggesting that the later phases may be diffracted or surface waves from a basin edge (Kawase 1996). Similar features of later phases near a fault were reported in damaged area in Kobe city (Yamanaka and Aoi 1996). Further analysis on dispersive features of the possible surface waves in the later phases is addressed as a future work for improvements of deep S-wave velocity models in the area.

Results in Nishihara village

An example of records obtained in Nishihara village during an event on May 05, 2016, with a depth of 11 km and M_J of 4.9 is shown in Fig. 6. The records obtained at MK13 are also included in this figure. The ground motion at NH05 is large and rich in the high-frequency contents, while the amplitudes at NH01 and 02 are small. The ratios of PGAs and PGVs at all the stations to those at the reference site of NH01 are shown in Fig. 7 together with differences of the seismic intensities. The standard

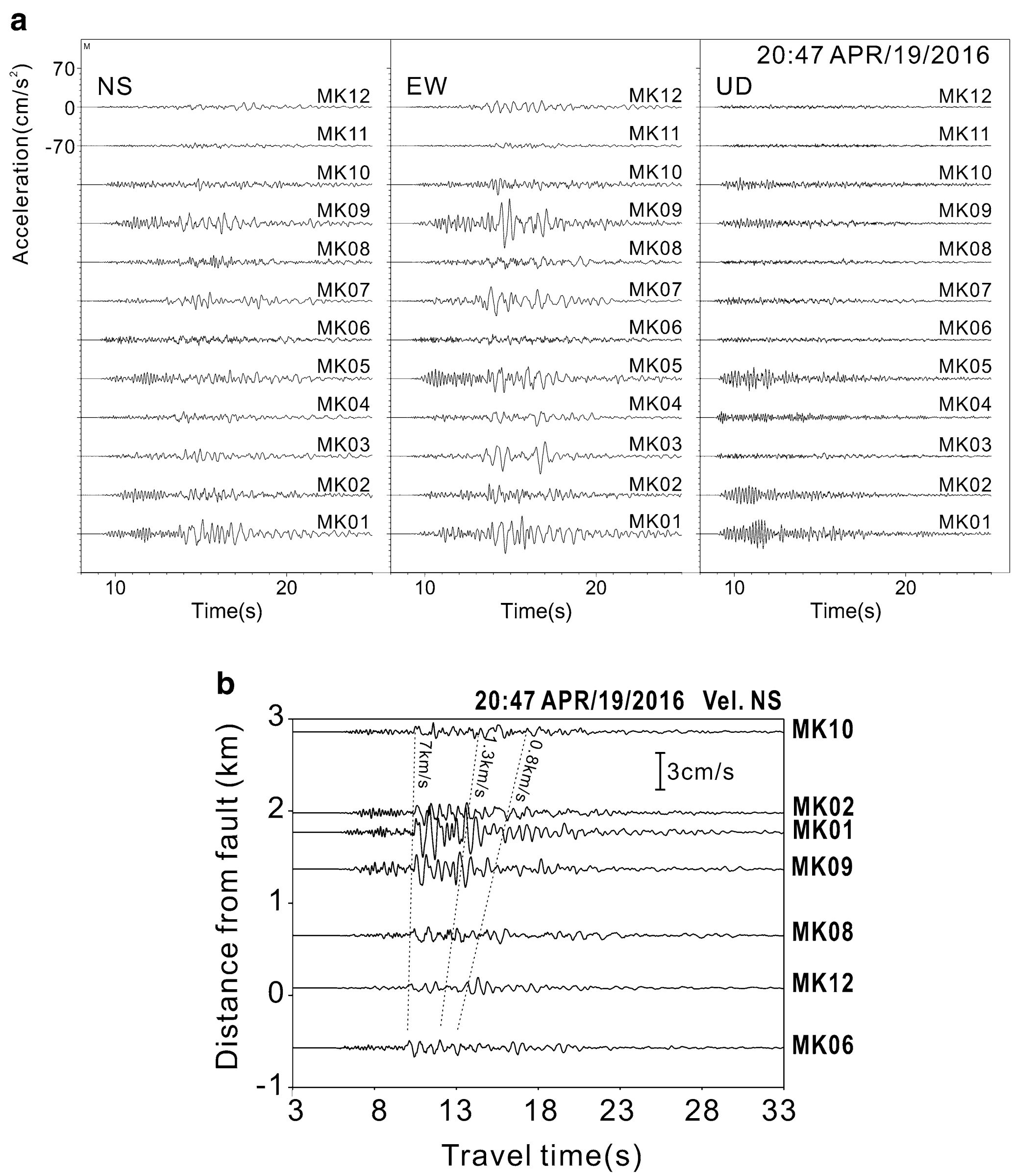

Fig. 3 Example of **a** observed acceleration records in Mashiki town during event at 20:47 on April 19, 2016 (depth: 11 km, M_J: 5.0), and **b** velocity traces filtered at periods of 0.05–10 s

deviations of the PGA ratios, the PGV ratios and the seismic intensity differences are 0.055, 0.103 and 0.025 on average, respectively. The ratios for the five stations are larger than one. In particular, the intensity difference at NH05 and MK13 is close to one suggesting a strong local amplification.

Spectral ratios are also displayed in Fig. 8. The spectral ratios at NH04 and 05 are large in a wide period range from 0.2 to 1 s, while the ratio at NH02 shows lower amplitudes at periods of 0.5–1 s with a shorter-period peak than those of NH04 and 05. Since NH04 and 05 are located in Koga and Okirihata districts with heavy

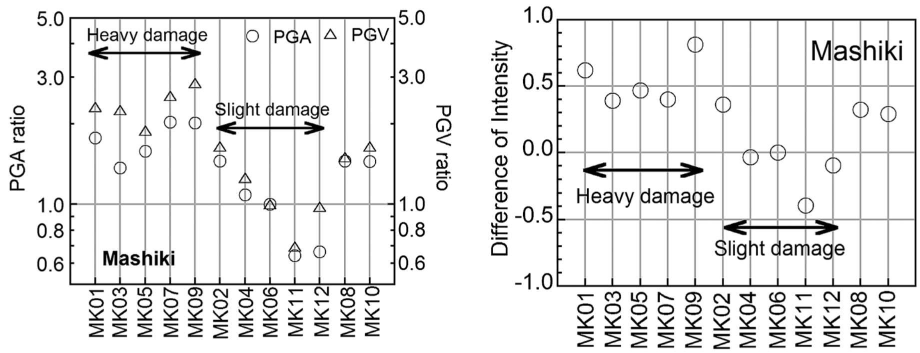

Fig. 4 Ratios of peak values (*left*) and seismic intensity (*right*) at each site to those at reference station of MK06 in Mashiki town

damage, the observed different features clearly suggest that the site effect is one of the reasons for the heavy damage in the two districts. The spectral ratio for NH03 is also large at a period of 0.4 s. This station is located very close to the intensity meter of Nishihara village. Our observations also suggest the significant effects of local soil on the large ground motion at this station. Sakai and Nakamura (2004) indicated an importance of 1-s motion to an estimation of structural damage. The absence of the amplification at a period around 1 s in the ratio may be one of the main reasons for the moderate damage around NH03, in spite of the large peak at a period of 0.4 s.

Results in Minami-Aso area

An example of acceleration records in Minami-Aso area is shown in Fig. 9. These records were obtained during an event with a depth of 11 km and an M_J of 4.9. The ratios of PGAs, PGVs and seismic intensity differences were also calculated regarding AS01 as the reference station. The standard deviations of the ratios of the PGAs and the PGVs are 0.025 and 0.038 on average, while that of the intensity differences is 0.041.

The ground motion at AS03 is slightly large with several later phases that make duration longer than the others. However, the peak values and the seismic intensity are not so different between the four stations in the area as shown in Fig. 10.

The spectral ratios are also displayed in Fig. 11. The ratio observed at AS03 with extremely heavy structural damage shows a peak at a period of 0.6 s. Although AS01 is located in the quarry mine where rock outcrop can be seen near the station, the ground motion and its spectra are similar to those of AS02 covered with Quaternary layers. A common trough can be seen at a period of 0.3 s in all the three ratios. This can be due to a peak in the reference spectra at AS01 and may be caused by effect of near-surface low-velocity layers over rock formation. This suggests a difficulty in the conventional spectral ratio approach using the reference station in the area.

Results in Kumamoto city

Figure 12 displays an example of the records obtained during an event with a depth of 13 km and an M_J of 4.1 at KC01–KC04 in Kumamoto city with some stations in Mashiki town for comparison. The ground motions at KC03 and 04 are large and elongated by later phases. Figure 13 displays Fourier spectra of horizontal records. Spectra at KC01 and KC02 have small amplitudes at periods longer than 0.5 s, while the other two stations in the Kumamoto plain have dominant peaks at periods of 0.6 s. These features characterized by the large later phases can be effects of sedimentary layers in the Kumamoto plain. This effect must be included in understanding of strong motion characteristics of the main shock in the area. Since all the stations were not located on neither rock nor firm soil, spectra ratios are not estimated in the area. Further study is necessary to estimate effects of the sediments in Kumamoto basin including the nature of the above-mentioned later phases.

Conclusions

We have observed earthquake ground motions due to aftershocks of the 2016 Kumamoto earthquake at 26 stations with different geological conditions in the damaged areas of Mashiki town, Nishihara village, Minami-Aso area and Kumamoto city. The preliminary analysis of the observed records clearly indicates strong effects of the local geological condition in the heavily damaged districts in Mashiki town and Nishihara village. Ground motion spectra at the stations in the severely damaged

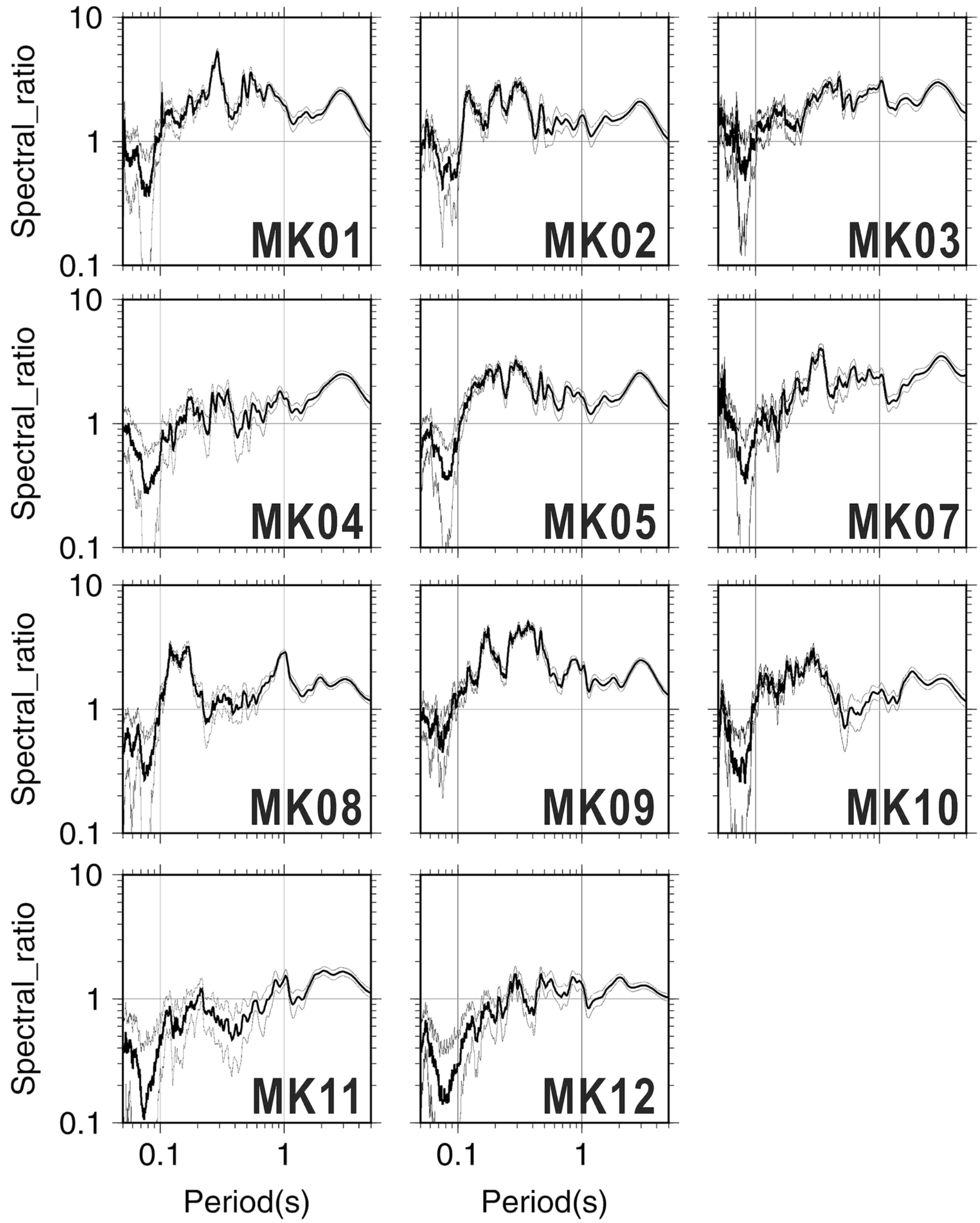

Fig. 5 Ratios of spectra in Mashiki town to that at reference site of MK06. *Thick* and *thin lines* indicate average ratios and their standard deviations, respectively

districts are characterized by the large spectral amplitudes at periods of 0.5–1 s. The peak ground velocities and the seismic intensities are also large at the sites. The seismic intensities at the stations in the damaged districts are large by an intensity of 1 at the maximum than those at the stations with the minor damage. In the other two areas of Minami-Aso area and Kumamoto city, site effects could not clearly be identified in

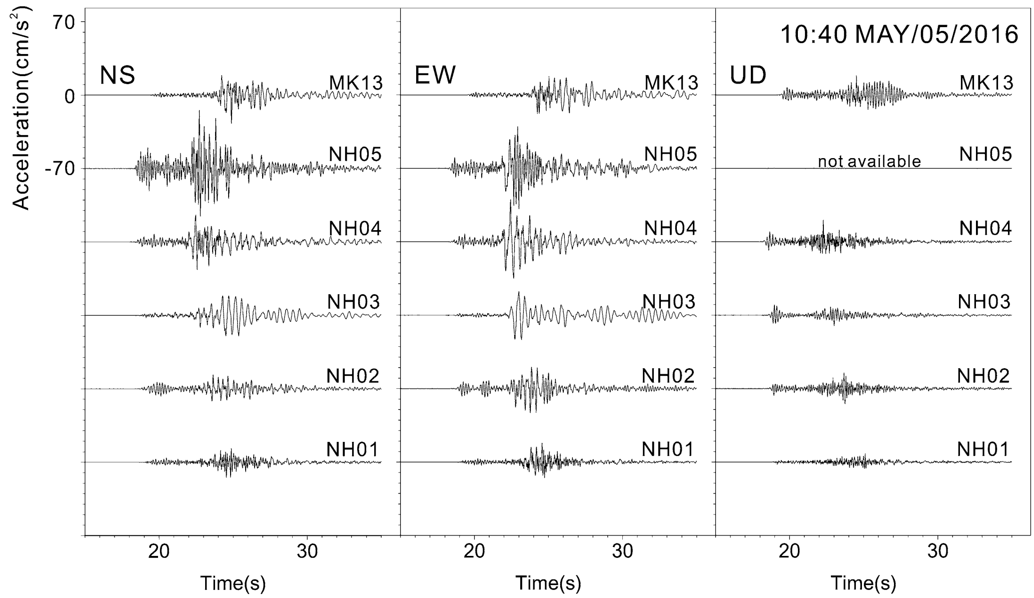

Fig. 6 Example of observed acceleration records at stations in Nishihara village during event at 10:40 on May 05, 2016 (depth: 11 km, M_J: 4.9)

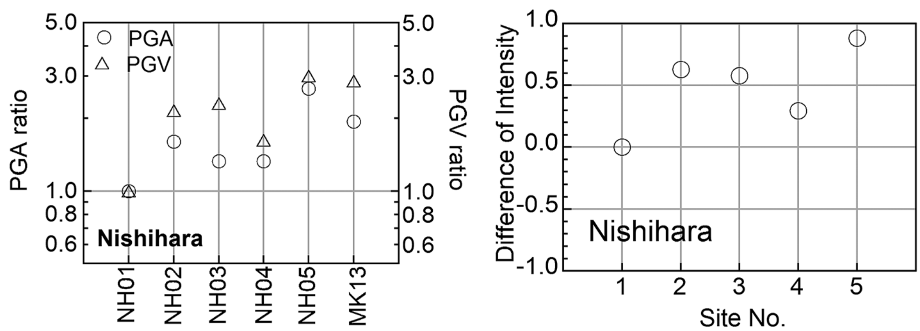

Fig. 7 Ratios of peak values (*left*) and seismic intensity (*right*) to reference station of NH01 in Nishihara village and MK13

the aftershock records in the conventional spectral ratio approach. It is also noted that the effects of attenuation of seismic waves with hypocentral distances are not contained in this conventional analysis. Further analysis of the acquired data using a generalized inversion (e.g., Bonilla et al. 1997) will be required to know a precise spatial distribution of the ground motion considering the effects of the geological conditions in the areas for understanding of reasons on the damage. S-wave velocity exploration of shallow soil was investigated in the area by Chimoto et al. (2016) using microtremor array measurements. Our results for site amplification will be quantitatively examined from theoretical ones from their results on S-wave profiles.

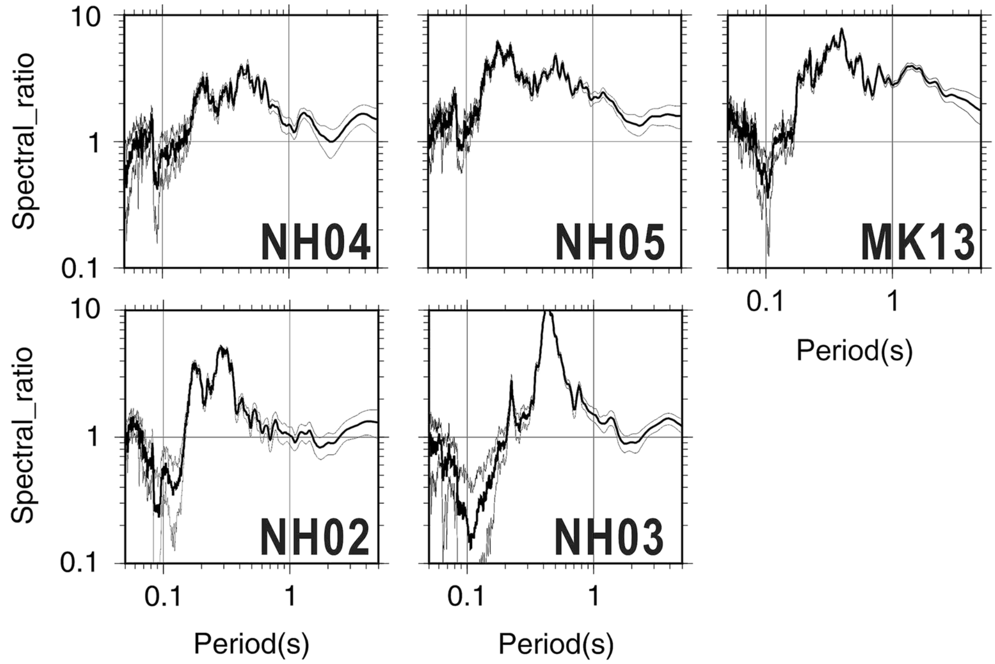

Fig. 8 Spectral ratio of records at stations in Nishihara village and MK13. *Thick* and *thin lines* indicate average ratios and their standard deviations, respectively

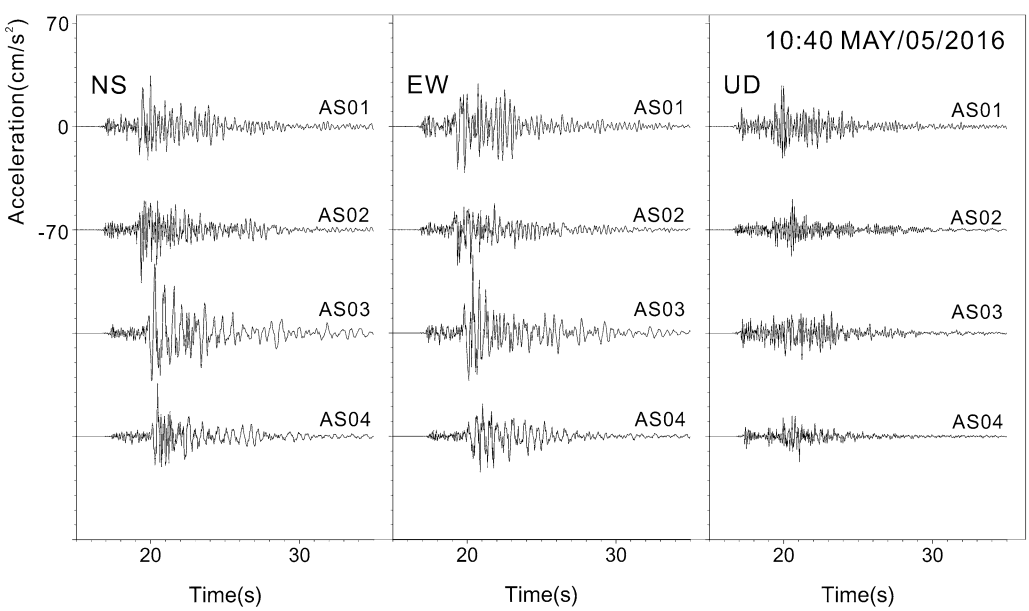

Fig. 9 Example of observed acceleration records at stations in Minami-Aso area during event at 10:40 on May 05, 2016 (depth: 11 km, M_J: 4.9)

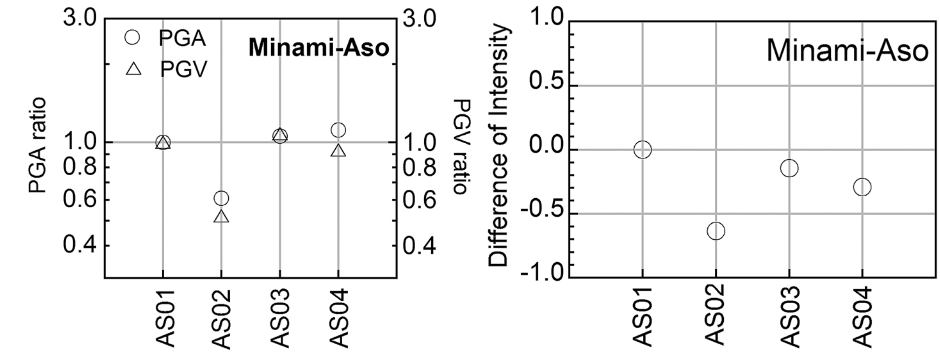

Fig. 10 Ratios of peak values (*left*) and seismic intensity (*right*) to reference station of AS01 in Minami-Aso area

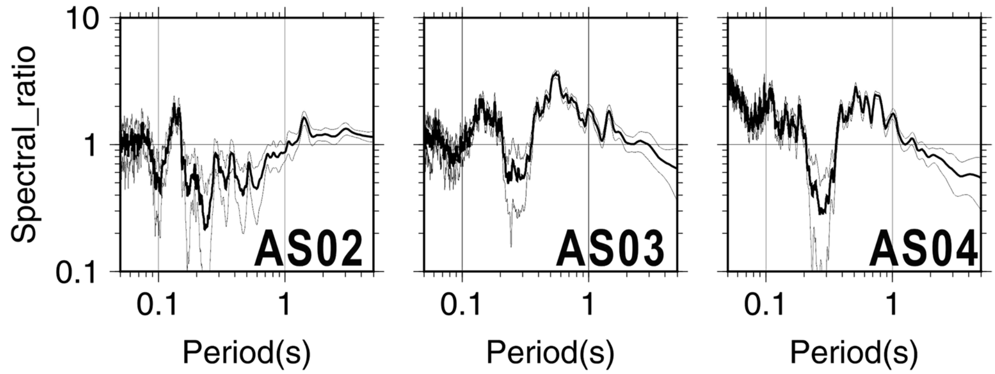

Fig. 11 Spectral ratios in Minami-Aso area. *Thick* and *thin lines* indicate average ratios and their standard deviations, respectively

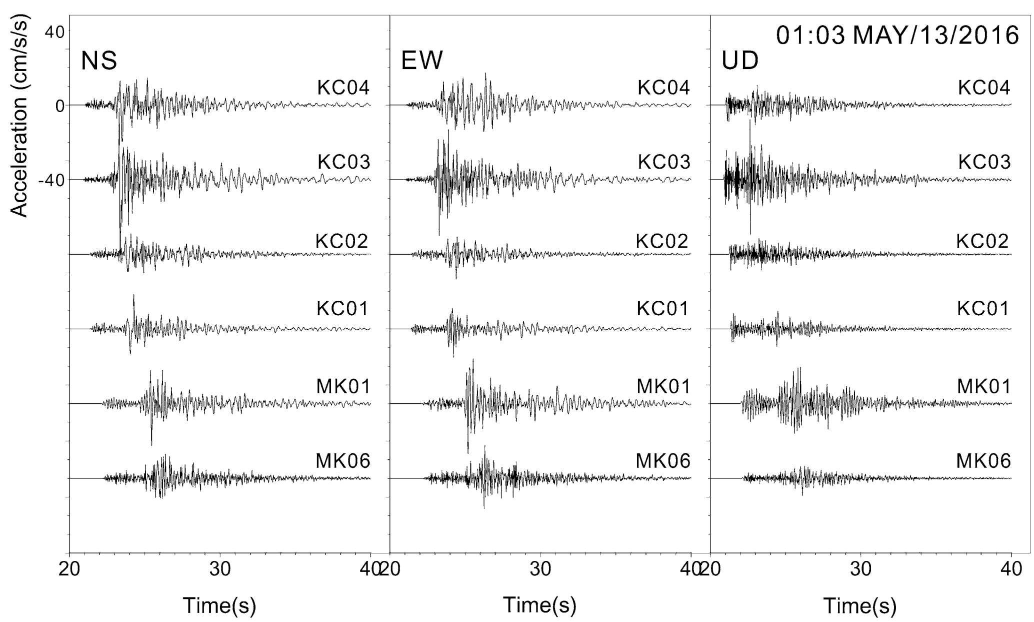

Fig. 12 Example of observed acceleration records at stations in Kumamoto city during event at 01:03 on May 13, 2016 (depth: 13 km, M_J: 4.1). Records at MK01 and MK06 are also displayed for comparison

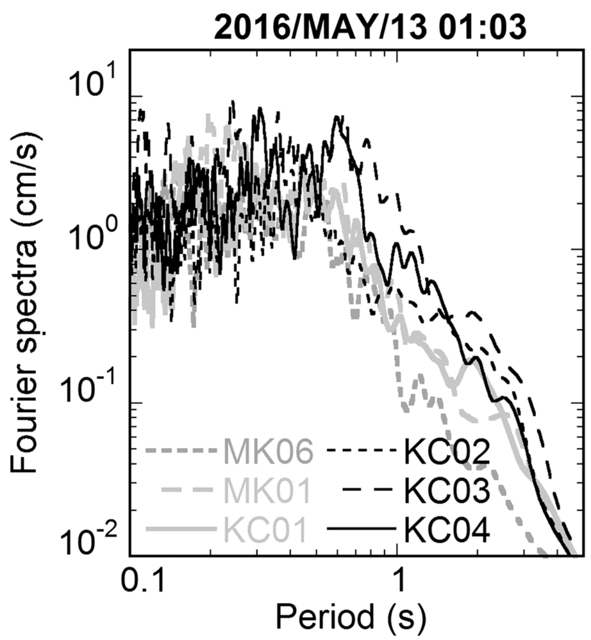

Fig. 13 Fourier spectra of horizontal records in Fig. 12

Authors' contributions
All the authors contributed to the field operation in the earthquake observations and the damage investigation. KC and HY processed the field data including earthquake records. HY wrote the manuscript through discussion with KC, HM, ST and NY. All authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

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