Source processes of the M 6 class earthquakes which occurred in northern Ibaraki Prefecture on 2011 and 2016

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<INTRODUCTION>

An M 6.3 earthquake occurred at 21:38 on December 28, 2016 in northern Ibaraki Prefecture. Since just after the 2011 off the Pacific coast of Tohoku Earthquake(M9.0), a significant increase in the shallow normal fault type seismicity, which had been extremely rare before the 2011 Tohoku earthquake, has been observed. Furthermore, the M 6.1 earthquake had occurred on March 19, 2011, within the area. According to the analyses of InSAR data, the crustal deformations of the 2016 and the 2011 earthquakes are observed in almost same area (GSI, 2017), so, it suggests that comparable size earthquakes have repeated in the interval of only about 5.7 years.

In addition, strong ground motions, those peak accelerations are about 1G, have been recorded during both earthquakes at the KiK-net station (IBRH13, Takahagi), therefore, those records are important to consider the ground motion level at the near faults. To consider these issues, the source process inversion analyses for the 2016 and the 2011 earthquakes are performed in this study.

<OUTLINE of ANALYSES>

The 16 stations of the K-NET and KiK-net (NIED) were used in these inversion analyses. Basically, identical stations were selected for the 2016 and the 2011 earthquakes. The acceleration waveforms were filtered between 0.03 and 0.8 Hz, and were integrated to velocity waveforms for the inversion analyses.

The source processes were inverted by the multi time window analysis (Yoshida et al., 1996, Hikima, 2012). The Green’s functions were calculated using 1-D velocity models, which were tuned by the waveform inversion method using the records of a small event (Hikima and Koketsu, 2005).

The fault planes for the initial models were configured by referring to the F-net mechanism solutions and distribution of the aftershocks, those were relocated using DD method (Waldhauser and Ellsworth, 2000). The parameters of the final models were determined by considering the degree of fitness between the observed and synthetic waveforms. The size of subfaults for the inversion analyses were set in 1 km.

<RESULT: 2016's earthquake>

The fault parameters are given as follows: the strike and the dip are 164 and 50 degree, and the length and width are 17 and 12 km, respectively. The focal depth is 10.3 km. The inversion result shows that the seismic moment is 9.7e17 Nm (Mw 5.9), and the maximum slip is about 0.7 m and the dominant focal mechanism is the normal fault type. The rupture propagated toward the northern shallow part mainly, and a large slip area (asperity) exists at 6 - 7 km apart from the hypocenter.

<RESULT: 2011's earthquake>

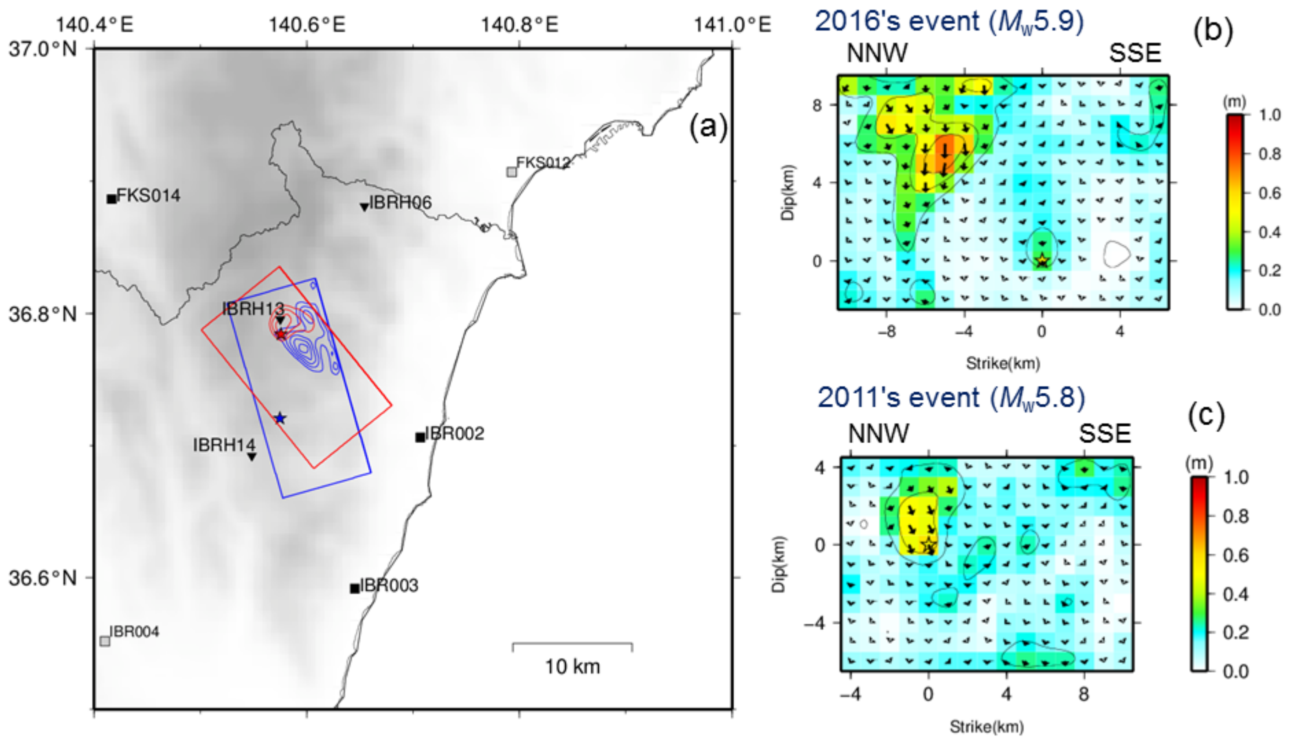
The fault parameters are set as follows: the strike and the dip are 141 and 40 degree, and the length and width are 15 and 11 km, respectively. The depth of hypocenter is 5.9 km. Dominant focal mechanism is normal fault type, and the estimated seismic moment is 7.0e17 Nm (Mw 5.8). The maximum slip is about 0.6 m and it is located near the hypocenter. The asperity covers the hypocenter and its slightly northern part. The amount of final slip on southern part of the fault plane is small.

<DISCUSSION>

The epicenter of the 2016's event is located at about 7 km south of the 2011's event. Though, it was revealed that the rupture of the 2016's event propagated toward the north and its asperity stands fairly near an asperity of the 2011's event. However, the strike and the dip of these events are different and it means that the fault planes of the events are not identical. Furthermore, the estimated slip distributions

show that the asperities of two events scarcely overlap each other. According to these results, it is deduced that the dominant slip areas of the 2016's and the 2011's events are different.
The KiK-net station (IBRH13), at which high accelerations were observed, is located adjacent to the asperities of these events. Especially, the asperity of 2011's event was recovered just below the IBRH13. The PGA of the 2011's and 2016's events was 1084 gal and 887 gal, respectively (3 components synthesized, from NIED's HP). This higher PGA of the 2011's event, although the magnitude is smaller than the 2016's event, is thought to be due to its closer distance from the asperity.

Keywords: Source process, Crustal earthquake, Strong motion, Repeating earthquake, Northern Ibaraki Prefecture earthquake



(a): Surface projection of the final slip distribution of 2016's and 2011's events. Blue denotes the 2016's event and red denotes the 2011's event. Squares and stars indicate set fault planes and epicenters, respectively. Contour shows slip area larger than 0.3 m, with interval of 0.1 m. Black marks denote KiK-net and K-NET stations.
(b), (c): Final slip distributions on fault planes of 2016's and 2011's events. The yellow stars mean hypocenters.

Estimation of the source location of the 16-April-2016 Oita induced earthquake with array analysis

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At the 14 April 2016, the mainshock of the 2016 Kumamoto earthquakes (M_{JMA} 7.3) occurred in Kumamoto Prefecture. After about 32 seconds from the origin, the induced event took place in Yufu, Oita prefecture. Looking on the seismograms, high-frequency phase is found following the phase of the mainshock, and can be clearly seen in the stations near the hypocenter. JMA determined the hypocenter of induced event by mainly picking S-wave arrival. Since phases of this event were contaminated due to the mainshock, the number of picked P-wave arrival was only four stations. Yoshida (2016) and Miyazawa (2016) also determined the hypocenter by picking out P- and S-wave arrivals in stations near the hypocenter. Nakamura and Aoi (2017) estimated the hypocenter location by the back-projection method using an acceleration envelope. In this study, we determine the source location using a horizontal slowness and an azimuth estimated by semblance method as a kind of array analysis. This method is employed for S phases observed in surround of the source region and a distance from there. We used the seismograms observed in K-NET, KiK-net and F-net of NIED, and seismic intensity stations of JMA and Oita prefecture. We set 5 arrays constructed each 3 stations. In the result of hypocenter determination using the azimuth and the slowness estimated in each arrays, the source location is 33.277N, 131.420E, 10.7 km depth. Seen from the hypocenter determined by JMA, the position by this study is off from the east side. Calculating PGA and PGV in 5 stations near the source, OIT009 in K-NET has higher PGA than other stations and highest PGV, where high site-amplification is modeled in Yufu basin. Although site-amplification is lower than OIT009, Tsurumi intensity station in JMA has largest PGA. These features denote that the source location might be located in the position of eastern side of the JMA’s location. Moreover we estimate moment magnitude using a flat level of S-wave displacement spectrum in 2 stations near the source. Modifying the site effect using observed spectrum in maximum aftershock (M_{JMA}5.4), we obtained M_w 5.5. Also, since the aftershocks did not hardly occur in surround the source location estimated by this study, we think that this area is the asperity of the induced event.
Acknowledgements: This work is partially supported by the Comprehensive Research on the Beppu-Haneyama Fault Zone funded by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan. We use strong motion records of NIED, JMA and Oita prefecture.

Keywords: Oita induced earthquake, Semblance method, Array analysis

On Application of Dynamic Rupture Simulations to Assess Possible Earthquake Source Parameters for Beppu-Haneyama Fault Zone, southwestern Japan

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For the strong ground motion prediction, increasing the physical constraints for source models is important to increase the predictability of the phenomena caused by possible future earthquakes. Currently standard approaches constrain the source models basically with the macroscopic characteristics of the slip-fault length scaling in a kinematic manner, where fault lengths, faulting styles and slip distributions are determined based on judgements of professionals. Relaying on such external information causes major difficulties of this approach since it contains large ambiguities due to observational limitations and, further, it is not necessarily physically based.
In this study we aim to utilize results of dynamic rupture simulations to provide the constraints of the source parameters targeting hypothetical future earthquakes generated along the Beppu-Haneyama fault zone (BHF), which exists as western continuation of the median tectonic line, southwestern Japan. The western part of BHF had been broken during the 2016 Kumamoto earthquake sequence. We constrained our dynamic model based on the regional stress field obtained basically by the seismological stress tensor inversions (Matsumoto et al., 2015) and newly modified fault geometry there, consisting of the three segments called the Funai-Asamigawa-Hotta (hereafter Funai), the Misa and the Hoyo channel from the west. The nonplanar geometry of these fault segments is treated by the spatio-temporal boundary integral equation method (ST-BIEM) with the fast domain partitioning method. The simulation results show, for example, the rake angles differ by up to approximately 30 degrees from the values assumed based on the recipe for kinematically predicting strong motion, namely 90 degrees for the Funai and Misa segments and the 180 degrees for the Hoyo channel segment. The dynamic rupture simulations may provide additional information for the strong ground motion prediction regarding the rupture/slip profiles, which are physical and natural outcome of the model.
This work is supported by the Comprehensive Research on the Beppu-Haneyama Fault Zone funded by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan.

Keywords: Beppu-Haneyama fault zone, Dynamic earthquake rupture models, Boundary integral equation method

Source, path, and site effects of intraslab and interplate earthquakes off Miyagi Prefecture in Northeastern Japan

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Kasatani and Kakehi (2014) made spectral inversion analysis of the intraslab and interplate earthquakes off Miyagi Prefecture in Northeastern Japan using K-NET strong ground motion data of NIED. Their result showed that the high-frequency levels of intraslab and interplate earthquakes with nearly the same depth are nearly the same, and that the high-frequency level depends simply on source depth and is higher for deeper source, independent of tectonic environments such as intraslab and interplate earthquakes. In previous studies, the view that high-frequency level of intraslab earthquake is higher than that of interplate earthquake has been widely accepted. On the other hand, some studies (e.g. Kato et al. (1999)) presented another view that high-frequency level depends simply on source depth, independent of tectonic environments, and high-frequency level is higher for deeper source. Result of Kasatani and Kakehi (2014) supported the latter.
Kakehi (2016) selected three events with different depths, whose epicenters are aligned linearly, from the events that Kasatani and Kakehi (2014) studied, and made an analysis of attenuation relation of peak ground acceleration using NIED K-NET and KiK-net strong ground motion data. He showed that the slope of the decay of attenuation relation of the deepest event is obviously steeper than those of the other two shallow events. This kind of depth-dependent trend of attenuation relation is frequently seen in previous studies.
In the spectral inversion of Kasatani and Kakehi (2014), common attenuation relation is assumed for all the events, independent of source depths. In this case, attenuation relation that is actually depth-dependent is attributed to source and site effects. Actually, the attenuation relations of the acceleration amplitudes with the site effects (obtained in the spectral inversion) removed shows similar gentle slope of decay for all of the three events. This means that in the spectral inversion of Kasatani and Kakehi (2014), the strength of attenuation is underestimated for deeper events, and therefore, the high-frequency level of source effect is also underestimated for deeper events.
When this underestimation of high-frequency level of deeper source is considered, high-frequency levels of deeper events will be higher than those obtained in Kasatani and Kakehi (2014). That is, validity of the conclusion itself that high-frequency level is higher for deeper source by Kasatani and Kakehi (2014) is supported, and the depth dependency of high-frequency level is more enhanced.
In the presentation, detailed report on source, path, and site effects of the intraslab and interplate earthquakes off Miyagi Prefecture is given, based on the evaluation of site effects from the inversion of "network of adjacent two station pairs" by Ikeura and Kato (2011) that does not assume attenuation functions.

Keywords: high-frequency level, intraslab earthquake, interplate earthquake, focal depth, attenuation relation, site effect

Analysis of Systematic Path Effects form Ground-Motion Variability Using Different Path-Bin Plans

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This paper describes the path diagram method should aim to the record-to-record residuals of a single earthquake instead of a single station, to solve the limitations of the bracket. We use 150 shallow earthquakes with moment magnitudes greater than 4.0 obtained from the Taiwan Strong-Motion Instrumentation Program network to build the Taiwan ground-motion prediction equations for peak ground acceleration and spectral accelerations with 5% damping for different structural periods. The record-to-record residuals are divided into small brackets in a path diagram for six distance bins and twenty-four azimuth bins. The mean residuals are estimated for each path bin, from which we can get 144 inter-path residuals for a source and compute a repeatable path-term for all inter-path residuals. Comparing the results with those obtained with the same data, but using the path diagram of a site, show that we obtain a lower remaining variance and the higher repeatable path-term with the 15° bracket of the path diagram approach for a source. The remaining unexplained intra-event standard deviations are 40-44% smaller than the record-to-record standard deviation for peak ground acceleration and spectral accelerations at periods of 0.3, 1.0, and 3.0 seconds. The results of path-to-path variability of each earthquake show that some earthquakes of small magnitude have a higher sigma because their source-to-site distances almost locate in the range of 0-50 km.

Keywords: GMPE, aleatory variability, strong ground motion, path effect, PSHA

The single-path standard deviation derived from ground motion records in Japan

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1. Introduction
The amplitude of a ground motion record includes aleatoric variability, even if the records observed at one site by the earthquakes with same magnitude and same location. It is important to clarify the characteristics of such variability in order to understand the accuracy of earthquake ground motion prediction. Using ground motion records from dense networks, several recent studies (e.g. Anderson and Uchiyama, 2011; Lin et al., 2011) have estimated the single-path standard deviations by removing ergodic assumption. Those studies are based on the difference between observed ground motion amplitude and a ground motion prediction model. Estimated variabilities may be affected by modeling error of applied ground motion prediction model. In this study, the single-path standard deviation have investigated directly from the amplitude ratio of pairs of ground motion records observed at one site by two earthquakes with same magnitude and same location.
2. Data and Method
The amplitude ratios of pairs of ground motion records by two earthquakes have been investigated. The two earthquakes satisfy the following conditions. 1) JMA magnitudes (M_J) are the same. 2) Focal mechanisms are similar. 3) Distance between hypocenters is 3 km or less. Pairs of ground motion records of K-NET and KiK-net by two earthquakes have been used. Hypocentral distances of records are 5 or more times of the distance between hypocenters of two earthquakes, and 200km or less. Maximum acceleration of the records at free-field exceeds 1 cm/s^2. As a result, 39,103 pairs of record by 696 pairs of earthquake were used for this study. The single-path standard deviation (*sigma*) estimated by variance of the natural logarithmic acceleration response spectrum ratio (*v*) of record pairs. *sigma*=$(\mathrm{Var}[v]/2)^{0.5}$.
The acceleration response spectrum was averaged of two horizontal components.
3. Results
Estimated *sigma* from all data was about 0.3 - 0.45 (Fig. 1). This result at period of 0.02 s was consistent with single-path standard deviations for maximum acceleration from previous studies (Morikawa et al., 2008; Lin et al., 2011). In Fig. 1, *sigma* was slightly large around the period of 0.2 s. According to comparison of *sigma* estimated from data of every magnitude range, the dominant period of *sigma* moved to the longer period depending on magnitude (Fig. 2). Since site and propagation path of each record pairs are the same respectively, the main factor of *sigma* is considered to be the differences in the source characteristics of two earthquakes. If the rupture processes of two earthquakes are different, the within-event variability of pairs of records from two earthquakes may be large around corner frequencies of two earthquakes. The dominant period of *sigma* from large earthquakes was longer than that from small earthquakes. The logarithms of the dominant period of *sigma* were proportional to about $0.4M_J$ (Fig. 3). Those characteristics of *sigma* indicate that the uncertainty of rupture process is one of the factors in single-path standard deviation.

Keywords: ground motion, response spectrum, variability, uncertainty

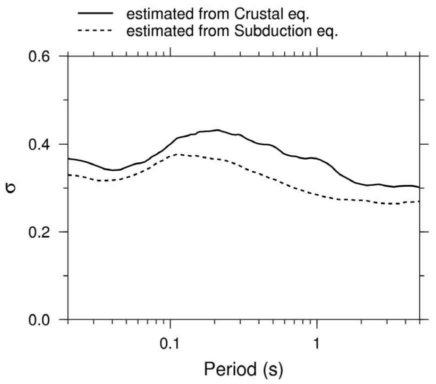

Fig. 1 Estimated single-path standard deviation σ. Solid line shows σ from data by crustal earthquakes. Dotted line shows σ from data by subduction earthquakes.

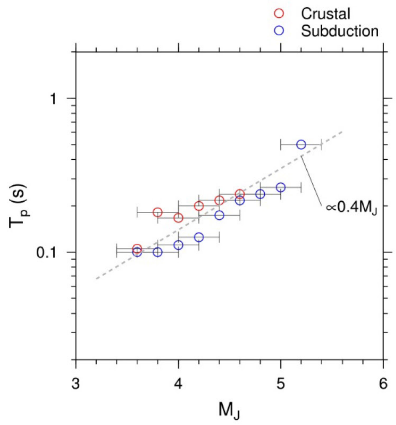

Fig. 3 Dominant period (T_p) of single-path standard deviation from data of every magnitude range. Red circle and blue circle shows T_p from data by crustal earthquakes and subduction earthquakes. Dotted line shows the approximate slope to M_J.

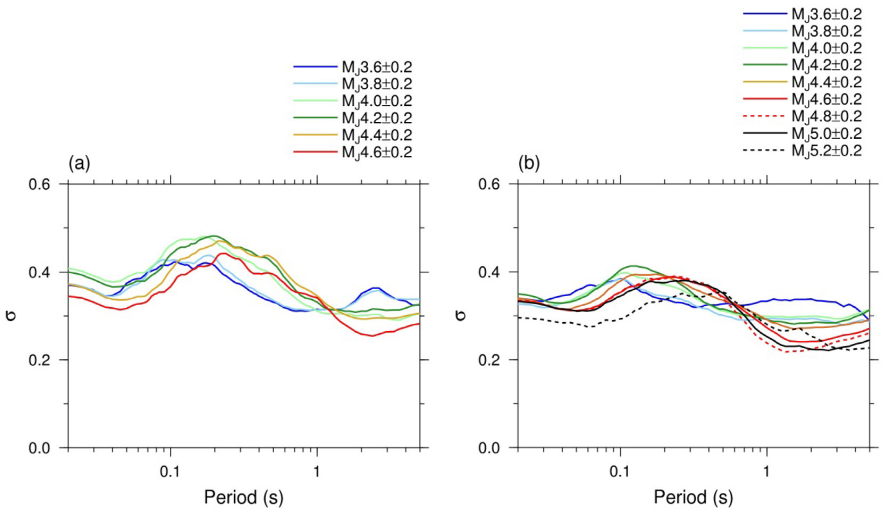

Fig. 2 Single-path standard deviation σ estimated from data of every magnitude range. (a) σ from data by crustal earthquakes. (b) σ from data by subduction earthquakes.

Attenuation characteristics of high frequency strong motions due to inland earthquakes in the Pacific coast of Tohoku region

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In order to decrease errors of empirical strong motion prediction, the author studied detail attenuation characteristics of strong ground motions observed at K-NET and KiK-net sites in the Tohoku and Kanto regions during events occurred in Hamadori region of Fukushima Prefecture and northern Ibaraki prefecture. Attenuation characteristics of strong motions from these events were investigated using base rock motion amplitudes converted from observed ones by cancelling site amplification effect using relative site factors. These relative site factors were evaluated by Ikeura and Tomozawa(2012) so as to satisfy all relative site factors between adjacent two sites in the K-NET and KiK-net observation networks in the region using least square method without attenuation functions. In this study, attenuation characteristics of high frequency strong motions due to the 23 March 2011 and 11 April 2011 Hamadori in Fukushima prefecture earthquakes and the 19 March 2011 and 28 December 2016 northern Ibaraki prefecture earthquakes, which epicenters were arranged almost in the N15E direction, were discussed based on amplitude distributions of converted base rock motions from these events with hypocentral distances. The distributions of the amplitudes of converted base rock motions at all sites showed clear attenuation curves for these all events. Results of investigations on distributions of the converted base rock motion amplitudes at the sites in the N15E direction from epicenter of each event were as follows: (1) Base rock motion amplitudes in the north region of epicenters were larger than in the south region, indicating source characteristics of northward stronger high-frequency radiations. (2) Attenuation of converted base rock motions in the direction of N15E showed quite weak Qs effect in the distances up to 100 - 150km from epicenters. (3) Steeper attenuation was observed in the distances over 150km in the south area of epicenters than in the north area.

Keywords: strong motions, inland earthquakes, attenuation characteristics

Non-Causal Zero-Phase Filters Underpredict NGA 2 GMPE’s for Long-Period, Near-Source Motions of Large Earthquakes

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The Lucerne record from the 1992 M7.3 Landers earthquake had motions too large to be accommodated by the San Bernardino Law and Justice Center. This is problematic because this structure was designed for maximum ground motion with triple pendulum base isolators. We investigated the predictions for 10-second response spectral displacements and found that NGA 2 GMPEs under-predict, specifically long-period, near-source motions from large earthquakes. The under-prediction may be due to the conventional data processing method used in the NGA ground-motion database, which is a non-causal zero-phase Butterworth filter at a corner frequency corresponding to the expected level of noise in the record.

Theoretically, a non-causal zero-phase filtered response is approximately half the value of the response with no filter. We can see this by filtering a unit step function, in which we get a response with half the amplitude of the original, unfiltered function. While non-causal zero-phase filtering leaves the acceleration unchanged, the effect of the corner frequency in this filtering is noticeable when we integrate twice to obtain the displacement. Therefore, because long period components of the recorded ground motion may contain valuable information, it is critical to choose the appropriate period of the non-causal zero-phase filter.

We examine the strong motion data from large earthquakes, such as the 1999 M7.7 Chi-Chi, 2015 M7.8 Nepal, 2016 M7.0 Kumamoto, and 2016 M7.8 New Zealand earthquakes. We apply the baseline correction to the uncorrected acceleration records, in which we account for the linear trend in velocity. Then, we integrate for the peak displacement. The same process is applied to the acceleration records that are non-causal zero-phase filtered at 10 seconds and 60 seconds. We compare the baseline corrected displacement responses of these earthquakes to the filtered ones. Ultimately, we take these broadband ground motion records containing long period effects, conduct both linear and nonlinear response analyses of tall buildings, and observe how static offset affects these responses.

Long-period ground motion in the Kanto basin during the 2016 Kumamoto earthquake

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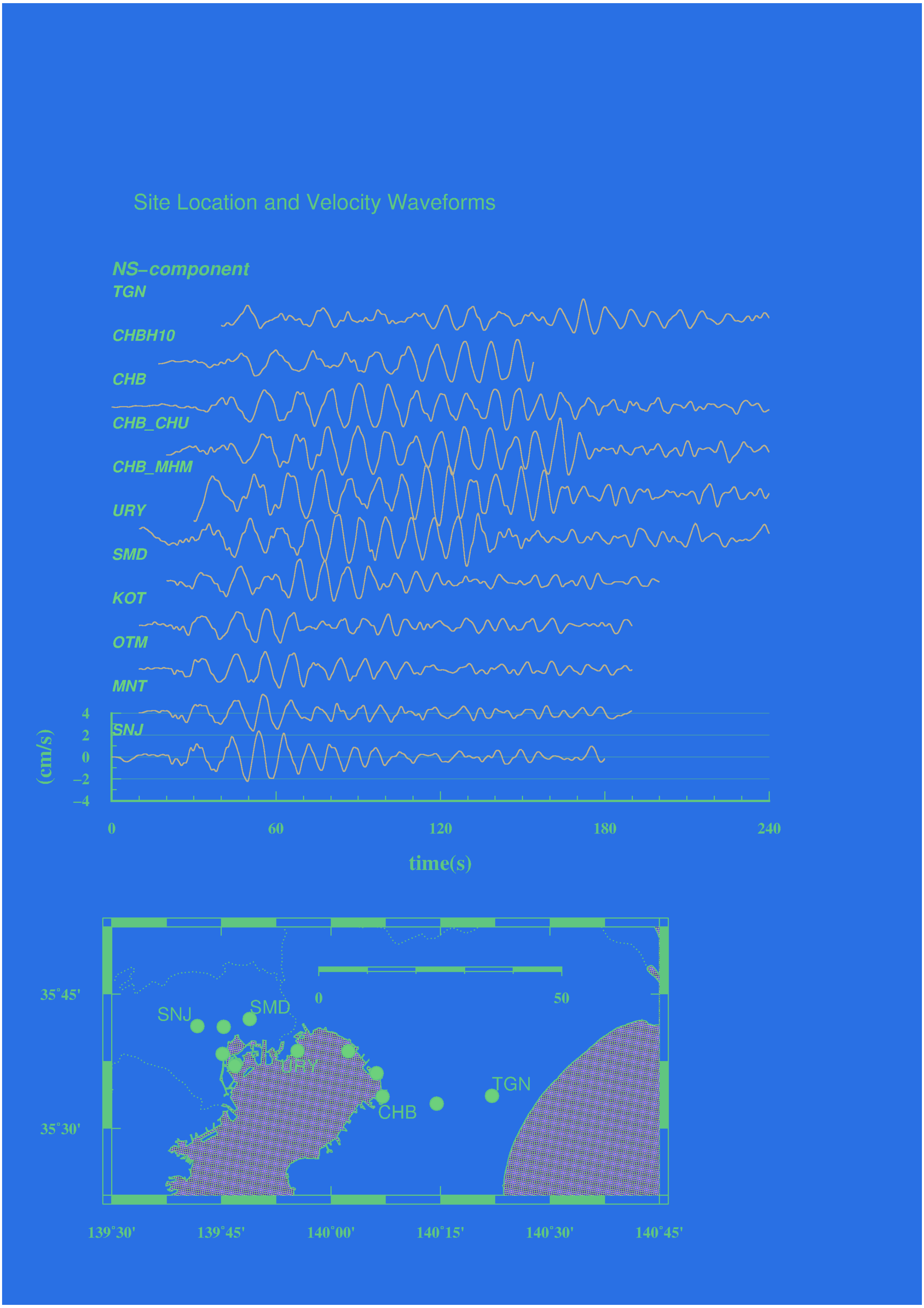
During the M 7.3 Kumamoto earthquake of April 16, 2016, the long-period ground motion was observed in the metropolitan area about 900 km from the epicenter. It is important to understand the characteristics of the seismic motion that incident to the Kanto basin and the seismic response of the basin to it for evaluation of the earthquake ground motion in the metropolitan area during a large earthquake in the western part of Japan.
First, in order to confirm the incident wave to the basin, the velocity traces of F-NET were examined from the vicinity of the epicenter to around the Kanto region. There was a remarkable wave group with the dominant period of about 10 seconds and the duration of about 60 seconds in the transverse component, and it was propagated to the Kanto basin with the apparent velocity of about 3.3 km/s. This wave group showed dispersion characteristics and is considered to be a Love wave. In addition, the waveform of the Kanto Mountains in the west side of the basin was similar to the waveform of the western part of the basin, and this group of waves is considered to be an incident wave to the basin.
Next, we examined the change of the waveform features of the observation point in the basin. Wave packets were amplified in the basin and the duration of wave packets was extended. However, the dominant period of the seismic motion was about 10 seconds at any observation point. It suggests that the influence of the incident wave is large. In addition, the amplitude of velocity response spectra at the period of 10 seconds tended to be larger toward the east side, which were about 2 cm/s at the bedrock in the west side of the basin, 5 to 10 cm/s in the western part of the basin, and 10 to 20 cm/s in the eastern part of the basin. It seems that not only the amplification by the low velocity sediment but also the extension of the duration are related to the amplification of the velocity response spectra.
The duration of the wave packet changes with the propagation of the wave packet and tends to be longer on the east side than the west side of the basin. From the multiple filter analysis of the velocity waveform, it is confirmed that the dispersion of the seismic waves influences the extension of the duration, and that the wave groups are more dispersed in the eastern observation point. The velocity waveform from Shinjuku (SNJ) to Chiba (CHB) and Togane (TGN) are shown in the figure. The duration of wave packet is about 90 seconds at Shinjuku (SNJ) in the west side, but over 180 seconds at Chiba (CHB) in the east side. The duration of the wave packet with the period of 10 seconds greatly changes in about 45 km.
Although the seismic ground motion of the north-south component was dominant in the western part of the Tokyo Bay, the large wave packets of the east-west component can be seen in the latter part of the wave traces in the east side. Examining the velocity locus shows that the dominant direction of vibration changes with the lapse of time. It suggests that the wraparound of surface waves due to the three-dimensional structure of the basin.
For this analysis, we used the records from Tokyo Electric Power Company, Japan Meteorological Agency and National Institute of Earth Science and Disaster Resilience (F-NET, K-NET, KiK-net). We used GMT for drawing figures.

Keywords: The 2016 Kumamoto earthquake, Surface wave, Long-period strong ground motion, Kanto basin


Site Location and Velocity Waveforms
NS–component
TGN
CHBH10
CHB
CHB_CHU
CHB_MHM
URY
SMD
KOT
OTM
MNT
SNJ
(cm/s)
4
2
0
–2
–4
0
60
120
180
240
time(s)
SNJ
SMD
URY
CHB
TGN
0
50
35°45'
35°30'
139°30'
139°45'
140°00'
140°15'
140°30'
140°45'

Observation and preliminary 3-D finite difference simulation of long-period ground motions (3 - 15 s) for the 2016 Mw 7.1 Kumamoto earthquake

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The Mw 7.1 Kumamoto earthquake, which occurred on 16th April, 2016, at 1:25 local time, is the largest inland earthquake to occur in Japan after the dense installation of K-NET and KiK-net strong-motion stations. Many previous studies based on the recorded ground motions from this earthquake noted that the non-existence of long-period structures such as high-rise buildings in the source area of the earthquake avoided potential risk that could be incurred due to the extremely large response spectra at periods of ~ 3 s to 7 s (e.g., Furumura, 2016). The occurrence of long-period ground motions near the source fault area of large earthquakes, particularly associated with the direct fault movement, has been well documented after the 1999 Chi Chi earthquake (Mw 7.6). On the other hand, if the size of earthquake becomes bigger such as the 1985 Mexico City earthquake (Ms 8.1), 2003 Tokachi Oki earthquake (Mw 8.3), 2011 Tohoku Oki earthquake (Mw 9.1), damaging long-period ground motions could be observed several hundred kilometers far from the source area. The 2016 Kumamoto earthquake also excited long-period ground motions at distant basins such as the Osaka basin which is located at a distance of about 400 km from the source area. Nonetheless, the motions were moderate and did not cause harmful effects on humans and infrastructures. The Kumamoto earthquake also reconfirmed that the long-period ground motions can propagate effectively in the north east region from the source area of the earthquake due to radiation pattern of the typical fault motions and crust-mantle structure in the region (Dhakal et al., 2016). In this paper, we describe the observed characteristics of long-period ground motions from the earthquake and compare a large number of recordings with synthetics from 3-D finite difference simulations. We employ the 1st grade subsurface velocity model reconstructed for the prediction of long-period ground motions by Headquarters for Earthquake Research Promotion and the source rupture model by Kubo et al. (2016) who used strong motion recordings within a distance of 100 km of the source fault for inversion. This study is expected to contribute to better understanding of the performance of the velocity and source models for the prediction of long-period ground motions from future big earthquakes.

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Keywords: Kumamoto earthquake, Long-period ground motions, Finite difference method

Generation conditions of long period ground motion in Kanto Basin

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Purpose of the study

In the Kanto Basin in Japan, the long-period ground motion with period between 3 to 10 s is strongly developed when large and shallow earthquakes occur nearby Tokyo. The cause of the long-period ground motion is explained by the seismic waves generated from the shallow earthquakes, propagating over long distances, and strongly amplified in the thick sedimentary layer of the basin. The edge of the basin is considered as a secondary seismic source to develop surface wave.

Recent studies reported that the level of the long-period ground motion was very large from the earthquakes in Niigata but is weaker from the earthquakes in Tohoku (Yuasa and Nagumo, 2012; Furumura, 2014). It is considered that various causes such as the influence of the 3-D structure of the basin, the propagation path, and the orientation of the earthquake to the Kanto Basin are involved in the generation intensity of the long-period ground motion. In order to investigate the cause of the earthquake-dependent development properties of the long-period ground motion in the Kanto Basin, we examined several possible causes based on the seismic wave propagation simulation of the 2004 Niigata Prefecture (Mw6.8) Chuetsu Earthquake (hereafter denote Chuetsu Earthquake).

Orientation of earthquake and generation of long-period ground motion

In order to evaluate the influence of the orientation of the earthquake source in the long-period ground motion generation in the Kanto Basin, we carried out a 3-D finite-difference method simulation of the seismic wave propagation using a sedimentary structure model in the area around Kanto (JIVSM; Koketsu, 2012). We examined the waveform from a set of virtual source based on the fault model of the Chuetsu Earthquake which are placed at equidistance from the Kanto Basin and the direction from northeast to southeastward. The result shows that the long-period ground motion is stronger when the source locates in the direction of the Niigata Chuetsu, and is weaker of the Tohoku. However, the difference was only about 4 times with the velocity response of the natural period of 6 s, which is insufficient to explain a large difference in observation (about 10 times; Furumra, 2014).

Radiation characteristics of surface waves from a source fault

Therefore, we investigated an another cause to examine the radiation characteristics of the surface wave from the source. Here, we conducted a set of wave propagation simulation of the Chuetsu Earthquake with modifying strikes of the source fault. As a result, the level of the long-period ground motion and the peak period of the response spectrum greatly changed with change of the fault strike, which is much larger than that of the source azimuthal effect. Also, it is confirmed that the response level of the long-period ground motion at 6 s becomes largest when the fault strike corresponds to that of the Chuetsu Earthquake (212 deg.).

“Basin-Induced Surface Wave” and “Basin-Transduced Surface Wave”

As a cause of the long-period ground motion in the basin, two different mechanisms, the “Basin-Induced Surface Wave” in which the surface waves generated by conversion from the S waves at the edge of the basin and the “Basin-Transduced Surface Wave” in which the surface waves traveling to the basin is amplified to develop other surface waves, are generally discussed (for example, Kawase and Sato, 1992; Kawase, 1993). In order to investigate the contribution of the basin-induced surface waves in the Kanto

Basin during the Chuetsu Earthquake, we examined by simulation using the model where the free surface is replacing with the rigid boundary condition in the propagation path in order to prevent the propagation of the surface wave to the basin. As a result, the amplitude of the long-period ground motion in the basin drastically decreased, and the velocity response level in the period over 3 s a are weakened to about 1/2. Therefore, it is concluded that the contribution of the basin-induced surface wave is small in generating the long-period ground motion, and is mostly occurred by the surface wave traveling into the Kanto Basin.

Summary and future works

From the above discussion, the strong long-period ground motion observed in the Kanto Basin during the Chuetsu Earthquake was due to the two facts that the surface wave was radiated strongly in the Kanto direction from the source and the surface wave propagated very efficiently to the basin through the propagation path. On the other hand, for the Tohoku earthquake, the opposite situation is conceivable, i.e., the inefficient radiation of the surface wave from the source, and strong attenuation of the surface wave in the propagation path along the Pacific Ocean to the Kanto Basin.

Keywords: long-period ground motion, Kanto Basin, surface wave

Spatial distribution of ground-motion variability in broadband ground-motion simulations

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Ground-motion prediction for a scenario earthquake requires evaluation of both the average ground-motion level and ground-motion variability due to model uncertainties.
This study aims to evaluate the ground-motion variability due to aleatory variability of the source parameters by modeling ground motion of the 2000 Tottori earthquake (strike-slip type) and the 2004 Chuetsu earthquake (reverse-fault type).
The source models are based on the characterized source model by the “recipe” (HERP, 2016) with fault location, size, and geometry as given parameters. Aleatory variability for the three source parameters is considered: (1) asperity location, (2) rupture initiation point, and (3) seismic moment. Two asperities are randomly located on the fault with no overlapping. A rupture initiation point is chosen randomly from the 2 km grids on the fault. Seismic moment M_0 is sampled from a normal distribution in which the mean value is given by the M_0-S relation (S being the fault area) by Irikura and Miyake (2001) and mean+2σ equals to 2M_0. Short-period level A, another important parameter in the characterized source model, is derived from A-M_0 relation by Dan et al. (2001).
Ground motion for each earthquake is simulated by a hybrid approach; 3D FDM (Aoi and Fujiwara, 1999) for long periods (> 1 s) and the stochastic Green’s function method (Dan and Sato, 1998) for short periods (< 1 s), using a set of 50 source models and a 3D velocity model of J-SHIS v2 (Fujiwara et al., 2012). For the 2004 Chuetsu earthquake, simulations using a simple 1D stratified velocity model are also conducted in order to exclude the effects of the complicated subsurface structure around the source area.
From the ground-motion simulation results with 50 source models for each earthquake, standard deviation (SD) of ground-motion indexes, ln of 5% damped acceleration response (Sa), PGA, and PGV, are analyzed at 10 km interval mesh. Distance and azimuthal dependence of SD are observed; the characteristics of the spatial distribution of SD differ from short periods to long periods. It is also found that the spatial distribution of SD is largely distorted by the complicated subsurface velocity structure for the Chuetsu earthquake.
As a step toward constructing a model of ground-motion variability in ground-motion prediction for a scenario earthquake, we attempt to fit the SD, each for strike-slip type and reverse-fault type, with a simple regression model using the fault distance and directivity parameters.
Effects of variability in other source parameters, such as rupture velocity and source time function, should be studied in our future works. Modeling variabilities in such source parameters requires investigation in physics- or empirical-based criteria.

Keywords: ground-motion prediction, ground-motion variability, source parameter, uncertainty

Broadband strong motion simulation for the Beppu-Haneyama Fault Zone based on the recipe

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We studied strong ground motions of hypothetical earthquakes along the Beppu-Haneyama Fault zone. Synthetic ground motion has been calculated with a Hybrid technique composed of a stochastic Green's function method (for HF wave), a 3D finite difference (LF wave) and 1D amplification calculation. Fault model consists of three fault planes, "Funai", "Misa", and "Hoyo strait", is employed, where the locations are determined from reflection surveys and active fault map. The rake angles are calculated with a dynamic rupture simulation considering stress filed around the faults (Ando et al, JpGU-AGU2017). Fault parameters such as the average stress drop, a size of asperity etc. are determined based on the recipe (Irikura & Miyake 2001, 2011). Three dimensional subsurface velocity structure model of Oita prefecture that was newly constructed based on the results of surveys and observations for the comprehensive research (Yoshimi et al., JpGU-AGU 2017) has been used.

This work is supported by the Comprehensive Research on the Beppu-Haneyama Fault Zone funded by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan.

Keywords: strong ground motion, active fault, hybrid method, Oita

Strong Motion Simulation considering the Fault Parameters based on Dynamic Rupture Simulation on the Beppu-Haneyama Fault Zone

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As part of the comprehensive research on the Beppu-Haneyama Fault, we have been studying the dynamic rupture process on the Beppu-Haneyama Fault (Ando et al., JpGU-AGU2017). In this study, we will focus on strong motion simulation considering the fault parameters based on the parameters that were derived from the dynamic rupture simulation on the fault zone. The fault model consists of three segments of the Beppu-Haneyama Fault zone, namely "Funai, Asamigawa, Hotta (hereafter, Funai)", "Misa", and "Hoyo strait (hereafter, Hoyo)" segments from west to east along the southern part of the Beppu Bay. When the dip angle for Funai, Misa and Hoyo segments are assumed to be 45, 45 and 75 degrees respectively, the rake angle are calculated to be about -67, -104 and -147 degrees respectively (Ando et al, JpGU-AGU2017). Also, we consider the time delay between the segments, especially the time delay between Misa and Hoyo segments because the two segments do not overlap with each other and how the rupture propagates would rely on the dynamic conditions on the faults. On the other hand, the three-dimensional velocity model that was newly constructed based on the results of surveys and observations for the comprehensive research (Yoshimi et al., JpGU-AGU2017). In this study, we use finite difference method (GMS, NIED) to calculate strong motion at the engineering bedrock considering the different fault parameters and hypocenters. This work is supported by the Comprehensive Research on the Beppu-Haneyama Fault Zone funded by the Ministry of Education, Culture, Sports, Science, and Technology (MEXT), Japan.

Keywords: Beppu-Haneyama Fault Zone, Dynamic Rupture, Strong Motion Simulation

Strong ground motions observed under the 2016 mid Tottori prefecture earthquake, Japan

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October 21st., 2016, an earthquake with Mj 6.6 hit mid area of Tottori prefecture, Japan. Earthquake swarms have been activated in the area since mid October in 2015. Large number of seismometers installed by the prefectural government, JMA(Japan Meteorological Agency), NIED(National Institute for Earth Science and Disaster Resilience) and Tottori University, observed strong ground motions in the area. Aftershock observations were also conducted just after the main shock at several temporary sites in the area with housing damages. From prompt analysis of the observed strong motions, it is understood that the ground motions were affected strongly by local site conditions, especially their predominant period caused by sedimentary response. The observed predominant periods at strong motion sites agree well with those estimated by previously conducted microtremor observations in the target area. Characteristics of the observed ground motion and structural damages due to the earthquake are reported considering effect of surface geology in the area.

Keywords: The 2016 mid Tottori prefecture earthquake, Strong Ground Motion, Surface Geology

Damage Islands in Mashiki Town from the 2016 Kumamoto Earthquakes

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The 2016 Kumamoto earthquakes caused serious building damage in the near-source regions. The first earthquake (foreshock, Mj6.5) occurred at 21:26, April 14 and the second event (mainshock, Mj7.3) occurred at 1:25, April 16. Since there was only a 28 hour interval between the two events, it is difficult to separate the damage of the two earthquakes from field surveys.

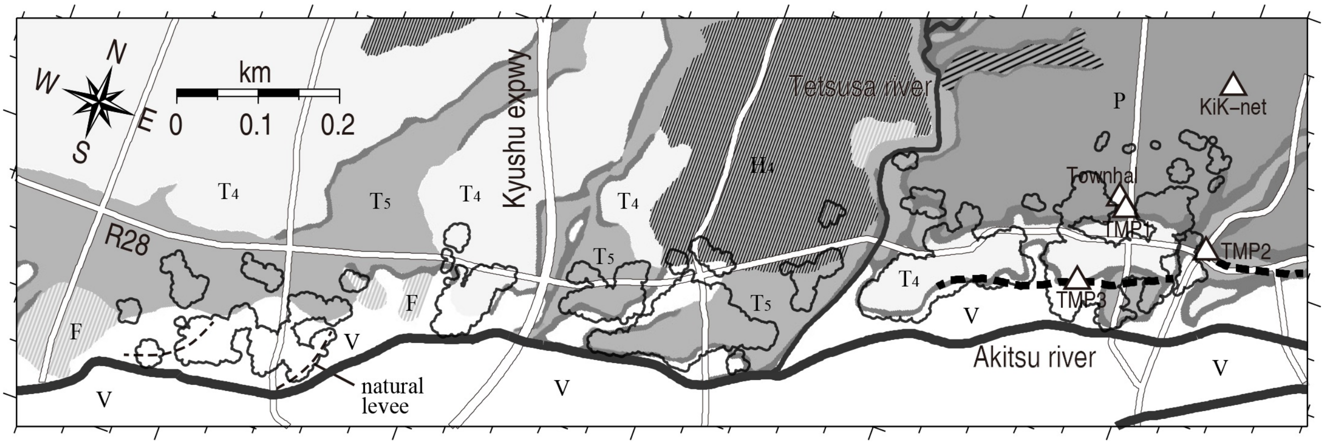
We analyzed aerial photos taken by the Geospatial Information Authority of Japan on the 15th and 16th of April and investigated the distribution of collapsed buildings along the Akitsu river. The photos cover the most severely damaged areas in Mashiki town. The two sets of photos taken between the foreshock and mainshock and after the mainshock, enable identification of the separate damage due to the foreshock and mainshock. The damage distribution is very heterogeneous, and the concentrations of severe damage occur in isolated areas resembling islands. The spatial pattern of the collapsed buildings due to the foreshock and mainshock were similar, but the number of collapsed buildings from the mainshock was 4 to 5 times the number for the foreshock.

The distribution of the collapsed buildings was compared with other information, such as the location of fault surface rupture, geomorphological map, and the location of the older built areas. The surface rupture was observed in the center of Mashiki town. The largest offset was about 40 cm along the southern edge of the concentrated damage area. Since this surface rupture was observed only after the mainshock, it is unlikely that the presence of the surface rupture generated the similar pattern of damage for the foreshock and mainshock in Mashiki.

Local geology in the survey area consists of the floodplain of the Akitsu river, multiple layers of river terraces, and an upper plateau of volcanic material. The heavily damaged area was in consistently in the lowest river terrace. The floodplain has the softest soil conditions in the area, but damage on the floodplain was much less than on the river terrace. The soft soil conditions are confirmed by microtremor array observations which showed thick sedimentary deposits with S-wave velocity less than 100 m/s on the floodplain. The observation that the most severe damage did not occur on the softest soil sites, is contradictory to many past studies. This unusual result needs further study to clarify the mechanisms of this damage distribution.

The damage islands correspond well to the distribution of the older built areas, which were constructed in the Meiji era (~1900s). Our photo analysis showed that the older buildings have a higher collapse ratio throughout the area. Therefore, building age and deterioration of the structures contribute to the damage distribution. The cause of the damage islands is likely due to a combination of the subsurface soil structure and age of buildings.

Keywords: kumamoto earthquake, building damage, strong motion



V: valley plain
F: fan and talus
T_4: terrace surface 4
T_5: terrace surface 5
H_4: low relief hill composed of pyroclastic flow deposits
P: surface of pyroclastic flow plateau

A Study on anisotropy of shear wave velocity near the source region of the 2016 Kumamoto earthquake -On the basis of seismic interferometry between ground surface and down hall of KiK-net observation-

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Some studies said that site amplification might affect destructive strong ground motions around Mashiki-Town according to results of aftershock observation and microtremor measurements. We evaluated subsurface structure models from microtremor array explorations, and explained that the resulted Vs structure models caused high amplitude of ground motions along NS direction, comparing between Mashiki-Town and just near a surface fault. The Vs models could not, however, reproduced strong motions along EW direction, and we found that different natural periods showed from each other horizontal direction at Mashiki Town (KMMH16). In this report, we investigated anisotropy of Vs near the source region of the 2016 Kumamoto earthquake, by applying seismic interferometry to KiK-net data.
We picked 3 stations, which are KMMH16, KMMH14 and KMMH03, as target sites. Resulted anisotropy parameters, which is (v_{fast}-$v_{slow)}$/v_{fast}, are 0.22 at KMMH16, 0.23 at KMMH03 and 0.15 at KMMH14. This anisotropy might not be explained by irregularity of subsurface structure, because there were few changes in results of seismic interferometry by binned back azimuth.
We expect directional difference of stress field due to plate motion as a factor of anisotropy, because Nakata and Snieder(2012) showed that the fast shear wave direction correlated with the direction of the plate motion in Tohoku district, Japan. In near future, we will apply this investigation to a number of stations, and will construct subsurface structure model for each polarization direction considering with other explorations, e.g. receiver function and phase velocity.

Keywords: the 2016 Kumamoto earthquake, seismic interferometry, KiK-net, anisotropy of shear-wave velocity

Velocity Structure Model of Sedimentary Basins in Toyama Prefecture, Japan, by Microtremor Array Measurements

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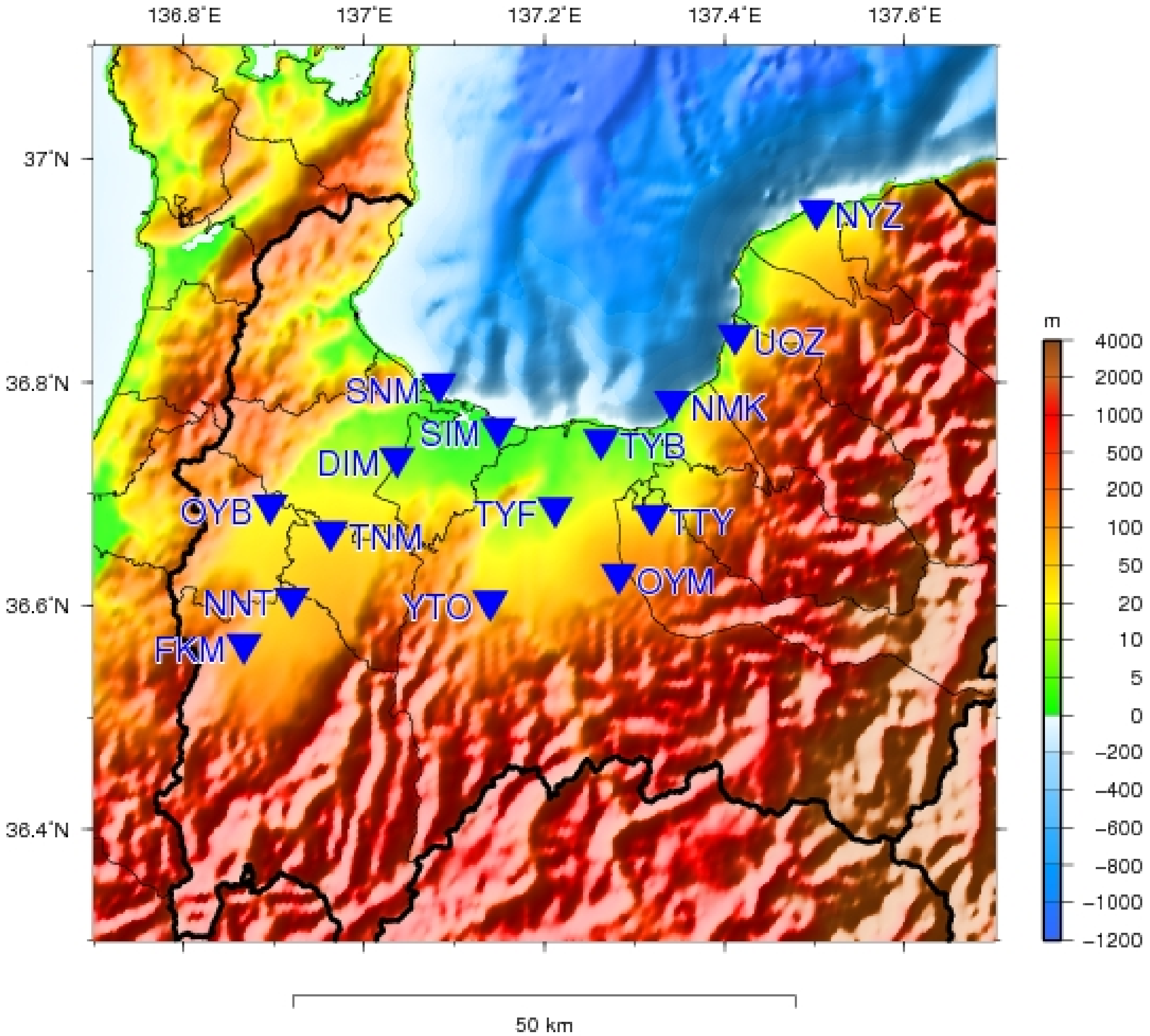
Sedimentary plains or basins in Toyama prefecture such as the Toyama plain, the Imizu plain, and the Tonami plain consist of alluvium fans and coastal plains (Fujii, 1992). These sedimentary basins are filled by thick sedimentary layers with thickness of more than several km formed during and after the back-arc rifting of the Sea of Japan in Neogene time (Toyama prefecture, 1992). The bedrock belongs to the Hida metamorphic belt. Many active thrust faults exist along boundary between hills and plains. Sea floor active faults were also identified around the Toyama Trough (Ishiyama *et al.*, 2014). A reliable basin velocity structure model is indispensable for predicting strong ground motions from those onshore and offshore active faults. However, geophysical exploration to survey the S-wave velocity structure down to the seismic bedrock is very few in this area. Thus, we have conducted microtremor array measurements and estimated the S-wave velocity structure models in this area.
The microtremor array measurements were conducted at 15 sites on 27-31 October 2015, 10-13 November 2015, and 9-12 November 2016 (see a map attached). These sites are close to strong motion stations of K-NET, KiK-net, JMA and Toyama prefecture in Nyuzen town (NYZ), Uozu city (UOZ), Namerikawa city (NMK), Tateyama town (TTY), Toyama city (TYB, TYF, YTO, OYM), Imizu city (SIM, DIM, SNM), Tonami city (TNM), Nanto city (FKM, NNT), and Oyabe city (OYB). In order to obtain the S-wave velocity structure continuously from the ground surface to the seismic bedrock, a set of array measurements consisting of several different sizes of array from about 20 m to 1.5 km was conducted at each site. Each array consists of seven Lennartz LE-3D/5s seismometers. The vertial component of microtremor was analyzed by the spatial auto-correlation method (SPAC), and we obtained the phase velocity in the frequency range 0.2-5 Hz. Sites on alluvial fans, NYZ, UOZ, TTY, TYF, YTO, OYM, TNM, FKM, NNT, and OYB have relatively higher phase velocity (0.6-1.0 km/s) even at 2 Hz or higher. On the other hand, other sites (NMK, TYB, SIM, DIM, and SNM) have relatively lower phase velocities (0.2-0.5 km/s).
We estimated the S-wave velocity structure model for each site from the obtained phase velocities assuming that the observed phase velocity represents the fundamental mode of Rayleigh wave. We referred to the nation-wide three-dimensional velocity structure model J-SHIS V2 developed by NIED (Fujiwara *et al.*, 2012), and we assumed a layered velocity structure model composed of homogeneous sedimentary layers and bedrock. The S-wave velocity for each layer was fixed at the value given by J-SHIS V2 model, and we estimated thicknesses of these layers to fit the observed dispersion curve by the genetic algorithm (Yamanaka and Ishida, 1998). We included an additional surface layer above the layer of Vs 0.6 km/s for sites where low phase velocities were observed. We also added a layer of Vs 0.75 km/s for some stations considering data fits. The estimated velocity structure models explain the observed phase velocities better than the present J-SHIS V2 model. The depth of seismic bedrock is approximately 5-6 km in the Toyama and Tonami plains, which is consistent with the deep seismic reflection and refraction survey KT01 crossing the Tonami plain and the Kureha hill by Ishiyama *et al.* (2016).
We are planning to improve the three-dimensional velocity structure model in this area combining our results and other information such as reflection and refraction surveys.
Acknowledgements: This study was conducted by the integrated research project on seismic and tsunami hazards around the Sea of Japan funded by the Ministry of Education, Culture, Sports, Science and

Technology, Japan. The field observation was conducted with help by people participating from Geo-Analysis Institute, Geo-Research Institute and DPRI, Kyoto University.

Keywords: Toyama plain, velocity structure model, microtremor array measurement



Modeling of the subsurface structure from the seismic bedrock to the ground surface for a broadband strong motion evaluation in Kanto Area. (part2)

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We have collected a lot of boring exploration and physical property data (mainly microtremor observation ones) in the past, which are important to especially evaluate seismic ground motion in period range from 0.5 s to 2.0 s, and have studied combining a shallow part with a deep one on a subsurface structure model, for the purpose of modeling subsurface structure so that we can evaluate broadband earthquake ground motion from 0.1 Hz to 10 Hz. In this paper, we will report the methods of modeling initial subsurface structure and S-wave velocity structure which incorporate period and amplification characteristics based on earthquake and microtremor observation records, in the whole area of Kanto including Tokyo, Japan.

In this research, initial geological models were developed and then subsurface structure models from seismic bedrock to ground surface were constructed by using records of earthquake observation and microtremor array observation. These models in Kanto area were improved in terms of broadband period characteristics in comparison with the previous integrated models. In addition, about computation with 1D multiple reflection method executed separately, the results were considerably improved in the vicinity of period 1 s which was important from the standpoint of disaster prevention. It can result from not only detailed modeling of shallow subsurface structure by collecting soil columns data, but also improvement of models by evaluating phase velocity and H/V spectral ratio based on microtremor observation, for the structure around engineering bedrock from Vs300 m/s to Vs500 m/s which were boundary layers between shallow and deep subsurface structure.

There are a number of problems in terms of model quality variability by region due to collection density of boring data at the time of development of initial geological models. But the method, which has using miniature array observation etc. and modifying the depth of engineering bedrock surface with geological information, can enable an S-wave velocity model to be stably improved around engineering bedrock in any region. In the near future, we will develop subsurface structure models in Tokai area and all over Japan.

Keywords: Strong motion evaluation, S-wave velocity structure model, Microtremor array, Borehole data

Estimation of bedrock depth by receiver function using strong motion data in the Kyoto basin

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We estimated R/V receiver functions of P waveforms of local earthquakes observed at strong motion stations in the Kyoto basin. Assuming a peak time of observed R/V receiver functions corresponds to the difference in arrival time between the direct P wave and the P-to-S converted wave (PS-P time) generated at the sediment/bedrock boundary in the Kyoto basin, we got the basin depth. The present Kyoto basin velocity model (Kyoto Prof., 2006) agreed with the obtained bedrock depth at most stations except several stations located near the basin edge. We modified the bedrock depth beneath each station. For validating that the peak time is corresponding to the PS-P time, we calculated theoretical R/V receiver functions using the discrete wavenumber method (Bouchon, 1981) with a double-couple point source in laterally homogeneous modified velocity model. Theoretical R/V receiver functions using the modified model showed good agreement to the observed R/V receiver functions.

Keywords: receiver function, Kyoto basin

Application of a fast calculation for full waves microtremor H/V based on diffuse field to identify underground velocity structures

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Based on Diffuse Field Approximation, the Full Waves (DFA-FW) Microtremor H/V Spectral Ratio (MHVSR) is expressed as the square root of imaginary part of the Green’s functions in the horizontal component to that in the vertical component. The DFA-FW MHVSR evaluated with the underground velocity structures composed of PS logging data is found to be the best matching with the observed MHVSRs at some KiK-net stations, compared with the transfer function of SH waves, H/V spectral ratio of fundamental mode of Rayleigh waves (ellipticity), and H/V spectral ratio of surface waves including contributions from fundamental and higher modes of both Rayleigh and Love waves excited by distributed surface sources. Therefore, the DFA-FW MHVSR should be applied to identify the underground velocity structures at the interested sites.

However, the conventional methods, such as discrete wavenumber method and contour integration method, is very time consuming in calculating the imaginary part of the Green’s functions. For a given layered medium, the DFA-FW MHVSR is found well approximated with only Surface Waves (DFA-SW) MHVSR of the “cap-layered medium” without fixed bottom which consists of the given layered medium and a large velocity cap layer in the deep added to the bottom of the given layered medium. Because the contribution of surface waves can be simply determined by residue theorem, the computation of DFA-SW MHVSR of cap-layered medium is significantly faster than that of DFA-FW MHVSR computed by other methods. The DFA-SW MHVSR of cap-layered medium, as a fast calculation for DFA-FW MHVSR of layered medium without cap layer, is then applied to identify the underground velocity structures above the bottom of the boreholes at KiK-net strong-motion stations.

The identified underground velocity structures between surface and bottom of boreholes were employed to evaluate DFA-FW MHVSRs which were consistent with the DFA-SW MHVSRs of corresponding cap-layered media. The earthquakes records at KiK-net stations provided the earthquake motions of H/V spectral ratios and spectral ratios of horizontal motions between surface and bottom of boreholes. The consistency between observed and theoretical spectral ratios for earthquake motions, indicated that the underground velocity structures identified from DFA-SW MHVSR of cap-layered medium were reasonable.

Keywords: microtremor H/V spectral ratio, diffuse field approximation, full waves, surface waves, cap layer, underground velocity structures

