Proceedings of the International Symposium on Engineering Lessons Learned from
the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan

STRONG MOTION ESTIMATION AT THE ELEVATED BRIDGES OF THE TOHOKU SHINKANSEN DAMAGED BY THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE BASED ON EXTENDED SITE EFFECTS SUSTITUTION METHOD

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ABSTRACT: The 2011 off the Pacific coast of Tohoku, Japan, earthquake caused significant damage to engineering structures, not only due to tsunamis but also due to strong ground motions. In this paper, an extended site effects substitution method was used to estimate strong ground motions at the site of damaged elevated bridges of the Tohoku Shinkansen in Kitakami City, Iwate Prefecture, Japan, for the 2011 main shock, with the site amplification and phase effects evaluated based on temporary aftershock observation records at the proximity of the site.

Key Words: Strong motion, site effects, aftershock observation, elevated bridges

INTRODUCTION

The 2011 off the Pacific coast of Tohoku, Japan, earthquake caused significant damage to engineering structures, not only due to tsunamis but also due to strong ground motions (*e.g.*, JGS 2011). It is important to estimate strong ground motions during the earthquake at sites where engineering structures were damaged for the purpose of investigating the damage mechanism.

Currently, Japan is covered with nationwide strong motion networks such as K-NET (*e.g.*, Aoi *et al*. 2004), KiK-net (*e.g.*, Aoi *et al*. 2004) and the Japan Meteorological Agency (JMA) network

(Nishimae 2004), with 1031, 688 and 637 stations, respectively, at the end of the year 2011. Thus, it is usually possible to obtain a record of strong ground motions within 20 km from a target site. The spatial variation of strong ground motions due to local geology, however, is quite significant (*e.g.*, Hata *et al*. 2011a) and it is often insufficient to employ the observed ground motions at a nearby station. Examples of the significance of the spatial variation of strong ground motions can also be found later in this article. It is necessary, therefore, to take into account the effects of local geology (site effects) to estimate strong ground motions at a particular site.

On the other hand, after a large earthquake, it is often possible to conduct aftershock observations and/or microtremor observations at a site of engineering interest (*e.g.*, Hata *et al*. 2011b). Thus, it is desirable to make an efficient use of the aftershock and/or microtremor observation results at the site of interest, in conjunction with the record of a large event at a nearby station, to estimate strong ground motions during the large event at the site of interest.

Conventional approaches to estimate strong ground motions at a site of interest using aftershock and/or microtremor records, fall into two categories. One of them is based on full strong motion simulation using fault models and aftershock records as empirical Green's functions. In these approaches, because the time history of strong ground motion is generated, one can obtain any ground motion parameters such as peak amplitude, duration, *etc.* based on the time history. In these approaches, however, the reliability of the result is obviously dependent on the quality of the fault model and it may not always be possible to obtain a fault model with sufficient reliability.

As the other category, a practical estimation method of strong ground motion (called 'site effect substitution method') was proposed by Hata *et al*. (2011c). The method is based on records of aftershocks both at the site of interest and at a nearby permanent strong motion observation station, and on a record of the main shock at the observation station. Because it focuses not only on the difference of site amplification factors but also on the difference of site phase effects between the site of interest and the observation station, it can compute time histories of strong ground motions at the site of interest with high accuracy (*e.g.*, Hata *et al*. 2011b; 2011c). Another advantage of the method is its simplicity. Unlike full strong motion calculations such as those based on the Stochastic Green's Function Method (*e.g*., Nozu *et al*. 2009), the method does not require a fault model of the large event. Therefore, it can be applied at an early stage of response to the large event even if a reliable fault model is not available.

The method, however, cannot be directly applied to a multiple-shock event such as the 2011 off the Pacific coast of Tohoku Earthquake, especially when contributions from two or more sub-events are remarkable for the site of interest. In this article, an extended site effect substitution method is proposed for solving this problem. In the extended method, the original method is applied to each sub-event successively. To validate the extended method, it is applied to strong motion records at permanent observation stations around the site of damaged elevated bridges of the Tohoku Shinkansen in Kitakami City, Iwate Prefecture, Japan, for the 2011 main shock. The estimated strong ground motions at the stations with the extended site effect substitution method are very consistent with the observed ones, indicating the validity of the extended method. As an application of the extended method, it was used to estimate strong ground motions at the site of the damaged bridges, with the site amplification and phase effects evaluated based on temporary aftershock observation records at the proximity of the site.

THE ORIGINAL AND EXTENDED METHOD

The original method

Fig. 1 shows the framework of the original method (Hata *et al*. 2011c). In Fig. 1, the original method is simply composed of three steps. First, the Fourier amplitude of strong motion at a target site (Site A) for a large earthquake is evaluated by correcting the Fourier amplitude at a nearby permanent strong-motion station (Site B) for the same event based on the difference of the site amplification factors at the two sites (Site A and Site B). Then, the Fourier phase of strong motion at the target site

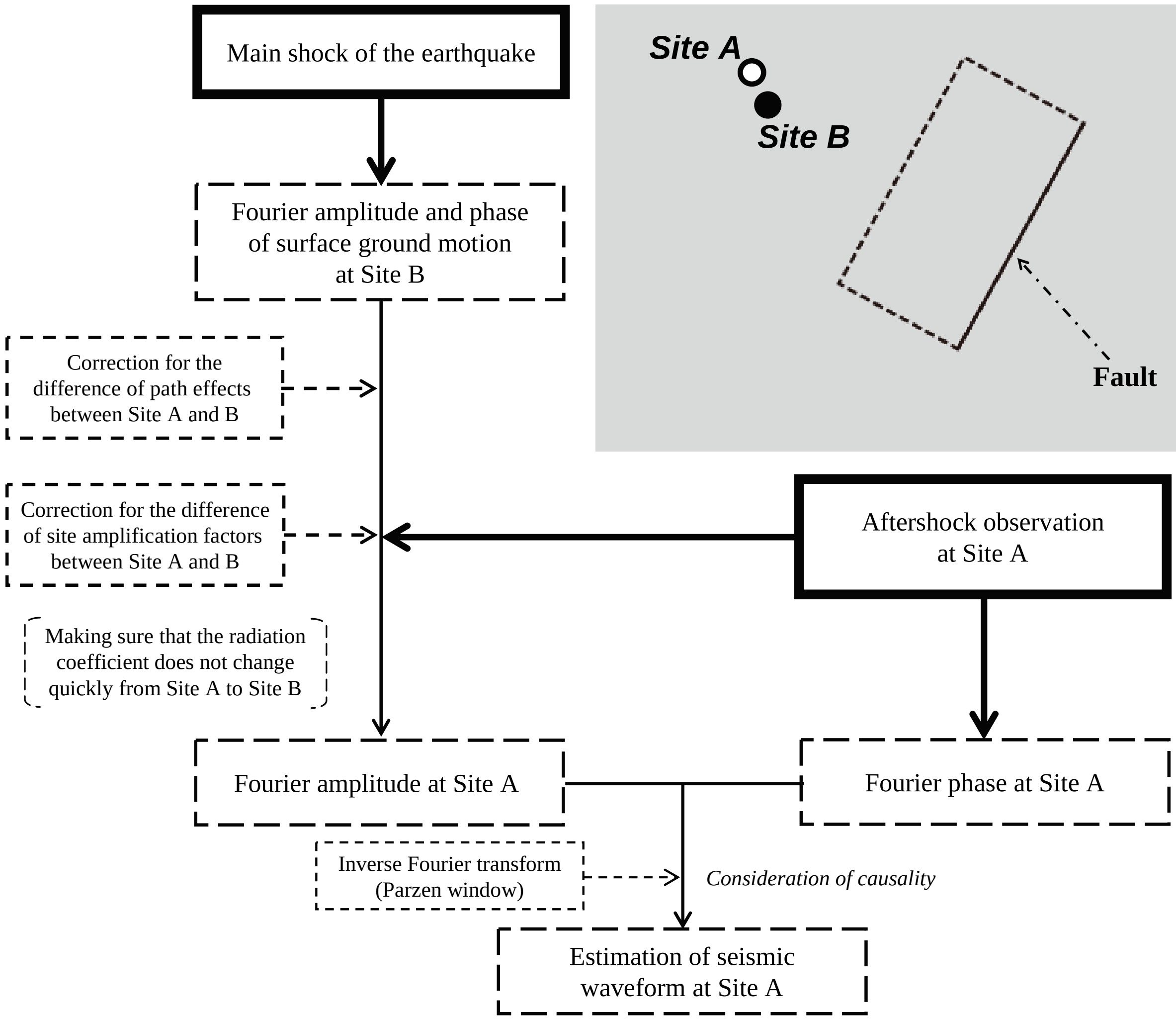

Fig. 1 The framework of the original method (Hata *et al*. 2011c)

(Site A) for the large earthquake is approximated by the Fourier phase at the same site (Site A) for a small earthquake that occurred close to the main rupture area of the large earthquake. Finally, an inverse Fourier transform is conducted to obtain the time histories of strong ground motions at the target site (Site A) for the large earthquake.

The extended method

One of the key assumptions of the original method is that the Fourier phase for the large event can be approximated by the Fourier phase for a small event, and, in fact, it has been shown that the assumption is appropriate for many of recent damaging earthquakes in Japan (*e.g.*, Nozu and Irikura 2008). It is obvious, however, that the assumption cannot be directly applied to a multiple-shock event such as the 2011 off the Pacific coast of Tohoku Earthquake, especially when contributions from two or more subevents are comparable for the target site (Site A). In fact, contributions from at least two subevents are quite evident in the waveforms observed in Iwate, Miyagi and Fukushima Prefecture, Japan, during the 2011 main shock (*e.g.*, Towhata *et al*. 2011). Even in such cases, one could still expect that the Fourier phase corresponding to each subevent is approximated by the Fourier phase for a small event (this part will be confirmed later in “Application to the 2011 off the Pacific coast of Tohoku Earthquake” section).

Thus, the authors extend the original method and propose a new method that can be applied to records for a multiple-shock event. Fig. 2 shows the framework of the extended method. In Fig. 2,

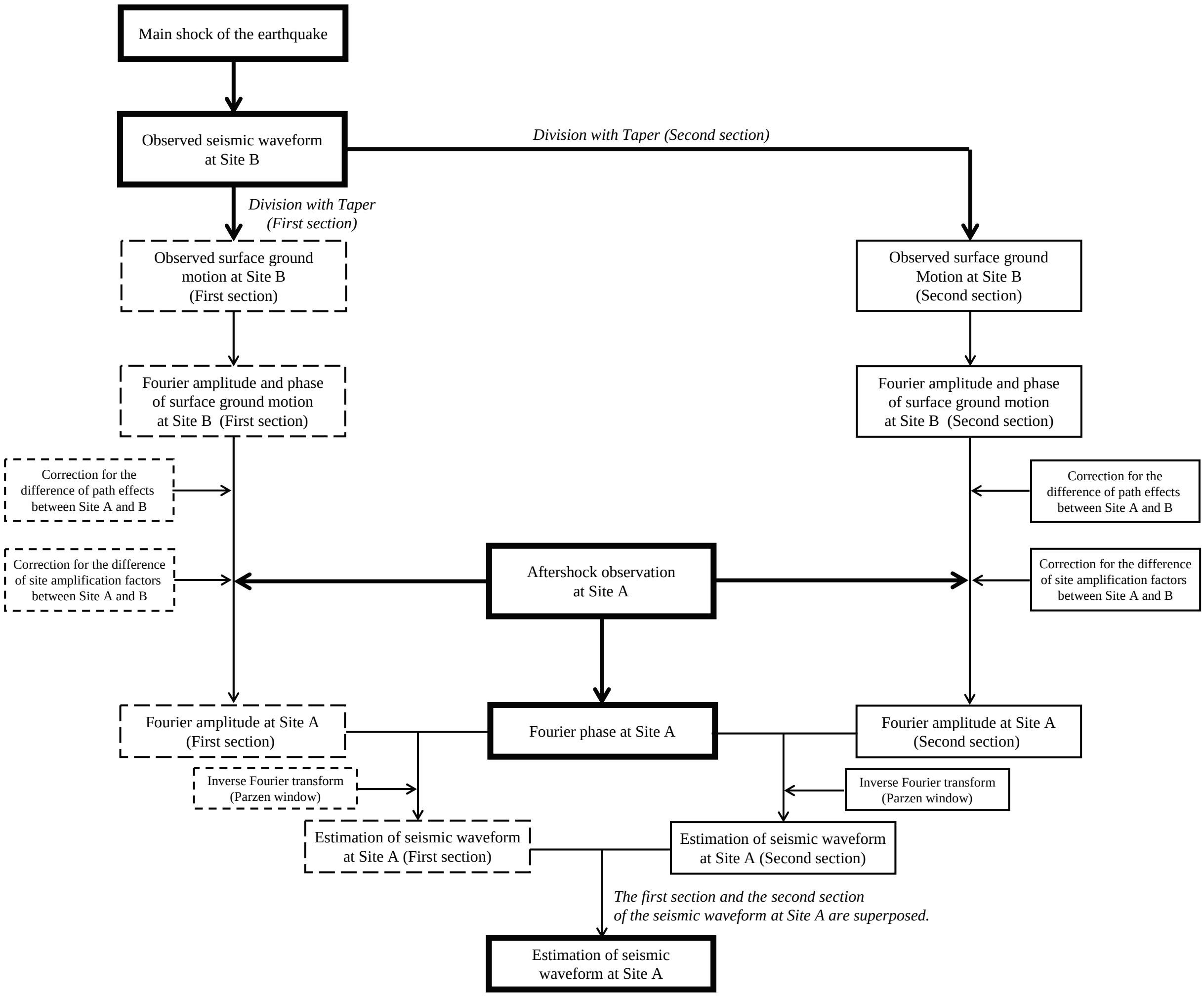

Fig. 2 The framework of the extended method

first, the waveform at Site B is divided into parts corresponding to each subevent (the first and the second sections) with a taper. Then, the original method (see Fig. 1) is applied to each section (the first and the second sections), and the waveform at Site A corresponding to each subevent is obtained. Finally, the waveforms are superposed to obtain the total waveform at Site A.

APPLICATION TO THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

Outline of application

In this chapter, to validate the extended method (called ‘extended site effect substitution method’), it is applied to the 2011 off the Pacific coast of Tohoku Earthquake. The validation is conducted by applying the method to estimate ground motions at strong motions stations and by comparing the estimated ground motions with the observed ones. Then the extended method is applied to estimate strong ground motions at the site of damaged bridges.

The earthquake occurred on 11 March 2011 off the Pacific coast of Tohoku and Kanto district, Japan. According to the Japan Meteorological Agency (JMA) unified source catalog, the hypocentral parameters are origin time 14:46 (Japan Standard Time); epicenter, 38.1°N, 142.9° E; depth, 24 km; and the moment magnitude M_W 9.0. According to the F-net of the National Research Institute for Earth Science and Disaster Prevention, the moment magnitude is M_W 8.7. As reported by Takahashi and Goto (2011), the earthquake caused serious damage to elevated bridges of the Tohoku Shinkansen in

Iwate prefecture, Japan (see Photo. 1). In order to analyze the damage mechanism, it is very important to evaluate the strong seismic motion at the elevated bridge site with high accuracy. The location of the hypocenter of the 2011 main shock and the site of the damaged bridges of the Tohoku Shinkansen is shown in Fig. 3.

Strong ground motions from the 2011 main shock were observed in nationwide strong-motion networks in Japan including K-NET, KiK-net, *etc*. A large amount of strong motion records was obtained in the earthquake. The locations of the strong motion stations around the damaged bridges of the Tohoku Shinkansen are shown in Fig. 4, with peak ground velocities (PGVs) and JMA seismic intensities (*e.g.*, Nishimae 2004). The list of the stations with abbreviations can be found in Table 1.

Strong ground motions observed at these sites show significant variability due to site effects. For instance, although TUW and KTK are close to each other, the PGVs and JMA seismic intensities at these sites are quite different (see Fig. 4), which indicates the significant difference of the site effects at these stations. In addition, strong ground motions observed at these sites are characterized by contributions from at least two distinct subevents as shown in Fig. 5 (a) and (b). Therefore, the records are quite suitable for the validation of the extended method. In the following, these records will be used for the validation.

Photo. 1 The damaged columns of an elevated bridge of the Tohoku Shinkansen (Takahashi and Goto 2011)

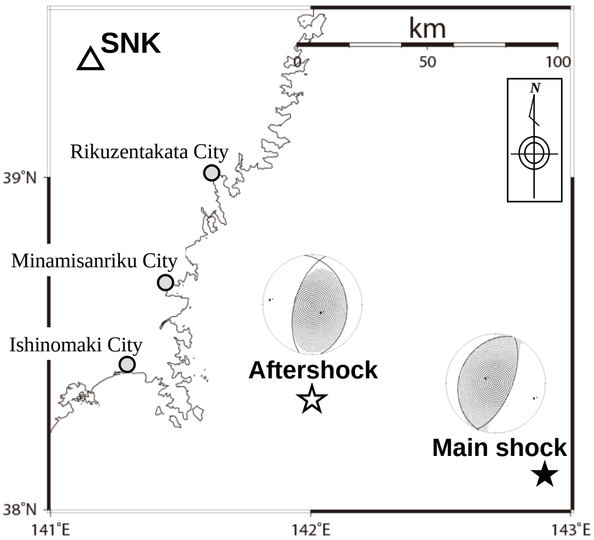

Fig. 3 The location of the damaged bridges

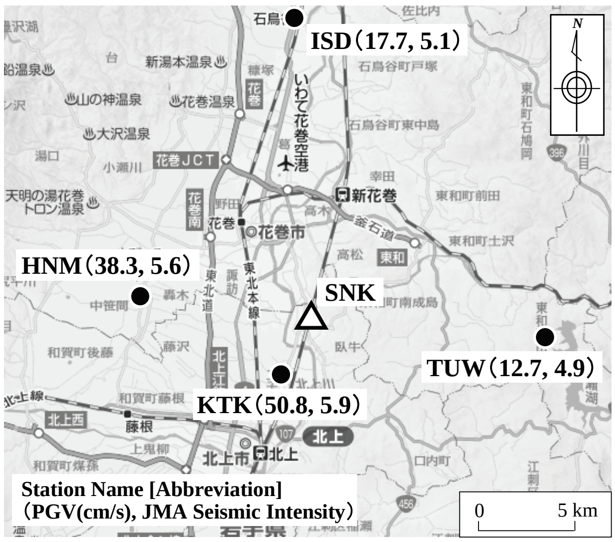

Fig. 4 The observation results of strong ground motions

Table 1 List of strong motion stations

Abbreviation	Station Name
SNK	Damaged piers site of Tohoku Shinkansen (Temporary aftershock observation site)
TUW	KiK-net Touwa
KTK	K-NET Kitakami
ISD	K-NET Ishidoriya
HNM	KiK-net Hanamaki-South

Table 2 Parameters for the main shock and the analyzed aftershock

	Date	Time (hh/mm JST)	Latitude* (deg.)	Longitude* (deg.)	Depth* (km)	M_W**	M_0** (N・m)	(strike, dip, rake)** (deg.)
Main shock	2011/03/11	14:46	N 38.103	E 142.860	24	8.7	1.07E+22	(200, 27, 88)
Aftershock	2011/07/13	00:37	N 38.330	E 142.007	47	4.9	2.64E+16	(195, 61, 103)

* After Japan Meteorological Agency (JMA)
** After F-net (see Data and Resources section)

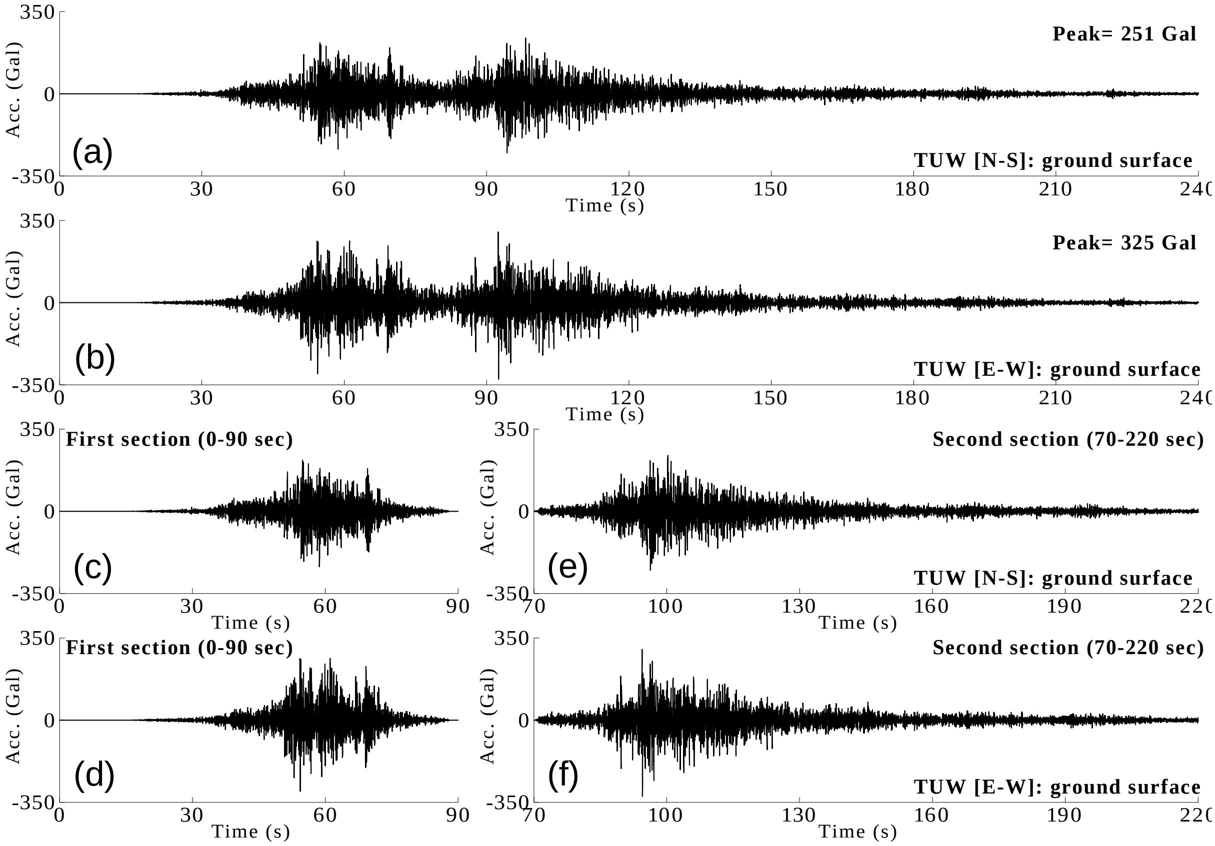

Fig. 5 The observed acceleration waveforms for the 2011 main shock at TUW

Although the main shock was observed at TUW, KTK, ISD and HNM sites, there was no strong motion observation station at the site of damaged bridges during the 2011 main shock. In this study, as shown in Fig. 6, temporary aftershock observation site (SNK) was created at the proximity of the damaged bridges, where commercial power supply was available. The observation was conducted for about 3 months from 18 April to 14 July, 2011. As the temporary observation results, a lot of seismic waveforms due to aftershock events were recorded. One of them is the July 13 aftershock (2011/07/13 00:37 off Miyagi Prefecture), which was observed at all sites including TUW, KTK, ISD and HNM (see Table 1). The source parameters of the main shock and the aftershock are listed in Table 2. The hypocenters and the focal mechanisms of the main shock and the aftershock are shown in Fig. 3. The July 13 aftershock will later be used for the evaluation of the site phase effects (see “Estimation of Fourier phase” section).

We estimate strong ground motions at KTK, ISD and HNM based on the records at TUW by means of the extended method. Then, by comparing the estimated and observed strong ground motions, the applicability of the extended method to the target area is investigated. Finally, using the extended method, strong ground motions at the site of damaged bridges during the 2011 main shock are estimated.

Division of waveforms

The observed acceleration waveforms at TUW are tapered off between 70 and 90 s to obtain the first section (see Fig. 5 (c) and (d)) and the second section (see Fig. 5 (e) and (f)) as shown in Fig. 5, each corresponding to different subevents.

Estimation of Fourier amplitude

Ratios of Fourier amplitude spectra at SNK with respect to TUW for 43 aftershocks are plotted using gray traces in Fig. 7. In Fig. 7, all of the spectra are smoothed with a Parzen window with a band width of 0.05Hz. In addition, the spectral ratios are corrected for the difference of the path effects, *i.e.*, the difference of the hypocentral distances for the 43 aftershocks at SNK and TUW. The black trace indicates the average for the 43 aftershocks. The authors think that it is important to average the Fourier amplitude ratios over several aftershocks to achieve robust estimation of strong ground motions. Although the ratios are around 1.0 from 0.2 Hz to 1.0 Hz, the ratios exceed 1.0 in the frequency range from 1.0 Hz to 6.0 Hz. In other words, in the frequency range from 1.0 Hz to 6.0 Hz, the site amplification factor for SNK is larger than for TUW.

The Fourier amplitude spectrum for the NS component at SNK during the 2011 main shock was obtained by multiplying the Fourier amplitude spectrum for the NS component at TUW with the average spectral ratio (see black trace in Fig. 7). The Fourier amplitude spectrum for the EW component at SNK was obtained in the same way from the EW component at TUW. The Fourier amplitude spectra for the horizontal components at KTK, ISD and HNM during the 2011 main shock were calculated in the same way, based on the records of the same 43 aftershocks. Fig. 8 shows the estimated Fourier amplitude spectra at KTK, ISD, HNM and SNK. In Fig. 8, the estimated spectra at KTK, ISD and HNM are compared with the observed ones. The agreement between the estimated and the observed spectra is quite satisfactory. In other words, the validity of the estimation method of the Fourier amplitude is well confirmed.

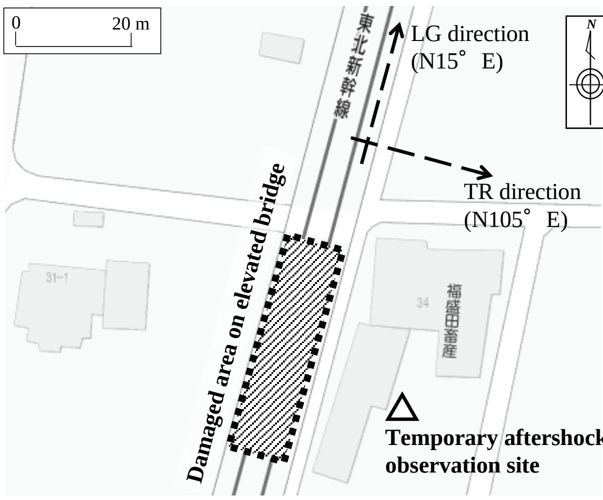

Fig. 6 Temporary aftershock observation site SNK

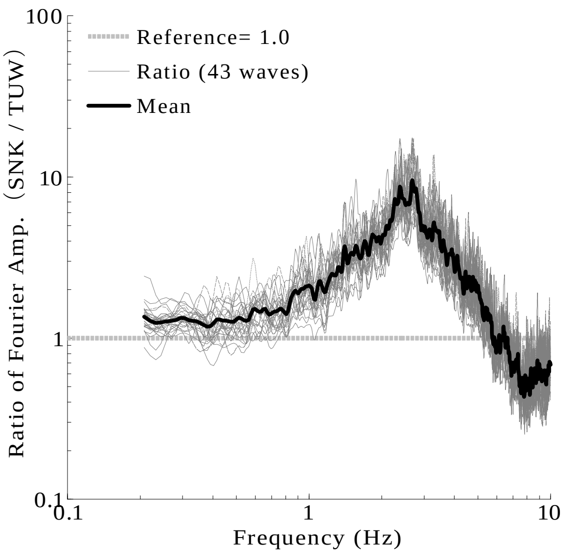

Fig. 7 The ratios of the Fourier amplitude spectra

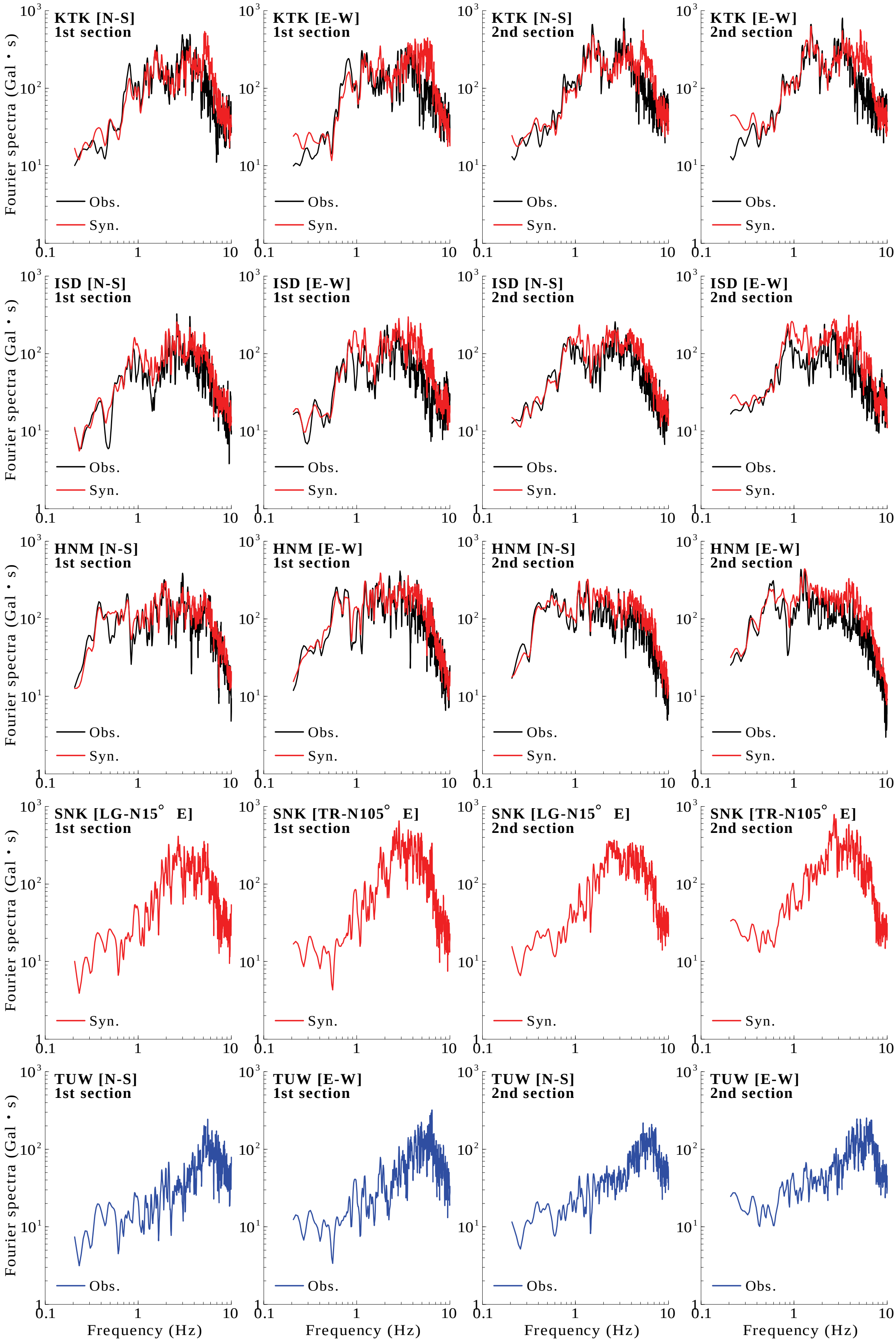

Fig. 8 The comparison of the observed and synthetic Fourier amplitude spectra for the 2011 main shock

Estimation of Fourier phase

In the site effect substitution method, it is desirable to select a small event that is close to the target event for the evaluation of Fourier phase. Therefore, in this study, the July 13 aftershock, shown in Table 2, was selected both for the first and the second sections, referring to its relative location to the main rupture area of the 2011 off the Pacific coast of Tohoku Earthquake (*e.g*., Kurahashi and Irikura 2011) (see Fig. 3). Validity of this selection can be confirmed as follows. In Fig. 9, the observed velocity waveforms for the 2011 main shock on the ground surface at TUW are shown as black traces, both for the first and the second sections. On the other hand, the red traces indicate the synthetic velocity waveforms with the same Fourier amplitude and the Fourier phase of the July 13 aftershock (see Table 2 and Fig. 3) on the ground surface at TUW. Both traces are band pass filtered between 0.2 and 3.0 Hz (Note that all of the velocity waveforms in this article are band pass filtered between 0.2 and 3.0 Hz). The left panels are for the first sections, and the right panels are for the second sections. In Fig. 9, we can recognize the similarity of the synthetic waveforms (red traces) to the observed ones (black traces), both for the first and the second sections. The similarity of the waveforms indicates that each of the first and the second sections of the main shock ground motion has almost the same Fourier phase as the aftershock ground motion, that is, although the 2011 main shock was a multiple-shock event, the Fourier phase for the first and the section sections of the main shock waveforms can still be approximated by the Fourier phase of the aftershock, at least for the target area. Thus, the Fourier phase of the aftershock at KTK, ISD, HNM and SNK is used in the following waveform estimation.

Waveform estimation

The first and the second sections of strong ground motions on the ground surface at KTK, ISD and HNM are respectively estimated by making use of the Fourier amplitude and the Fourier phase estimated above. Here, we generate causal time histories using the smoothing technique mentioned earlier. Finally, by superposing the first and the second sections, strong ground motions from the 2011 main shock on the ground surface at KTK, ISD, HNM and SNK are estimated. In the superposition, the relative arrival time of the S waves at TUW is considered.

The observed velocity waveforms (black traces) and the estimated velocity waveforms (red traces) at KTK, ISD and HNM are compared in Fig. 10 for the horizontal components. The similarity of all traces (see Fig. 10) indicates the applicability of the extended method. Thus, it is suggested that the extended method is applicable to the 2011 off the Pacific Coast of Tohoku Earthquake, at least for the target area. From an engineering point of view, it is quite important that a strong motion at a site without the record of the main shock can be estimated based on the record of the main shock at a nearby site even when the site effects are quite different for the two sites.

Fig. 11 shows the estimation results of velocity and acceleration waveforms at the ground surface at the site of the damaged bridges. Here, the velocity waveforms are band pass filtered between 0.2 and 3.0 Hz. Fig. 12 shows the estimated velocity response spectra for the horizontal components (Damping: 5%). Fig. 13 is the comparison of the design response spectrum (Damping: 5%) by Railway Technical Research Institute (RTRI 1999) and the estimated acceleration response spectra (Damping: 5%). In the natural period range from 0.12 s to 0.48 s, the estimated spectra are larger than the design spectrum. In future study, using the estimated strong motions, seismic response analysis for the elevated bridge shall be carried out.

SUMMARY AND CONCLUSIONS

After a damaging earthquake such as the 2011 off the Pacific coast of Tohoku, Japan, earthquake, there is an urgent need for the estimation of strong ground motions at sites of damaged structures that can be used for earthquake response analysis of structures, shake table tests and so on. Although the site effect substitution method proposed by the authors, is advantageous for the estimation of strong ground motions because of its simplicity, it cannot be directly applied to a multiple-shock event such as the 2011 off the

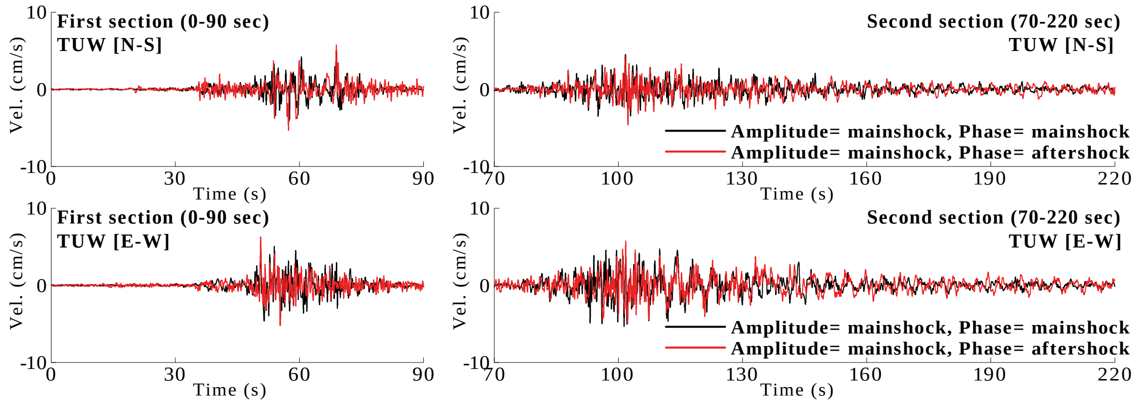

Fig. 9 The first and the second sections of the observed velocity waveforms

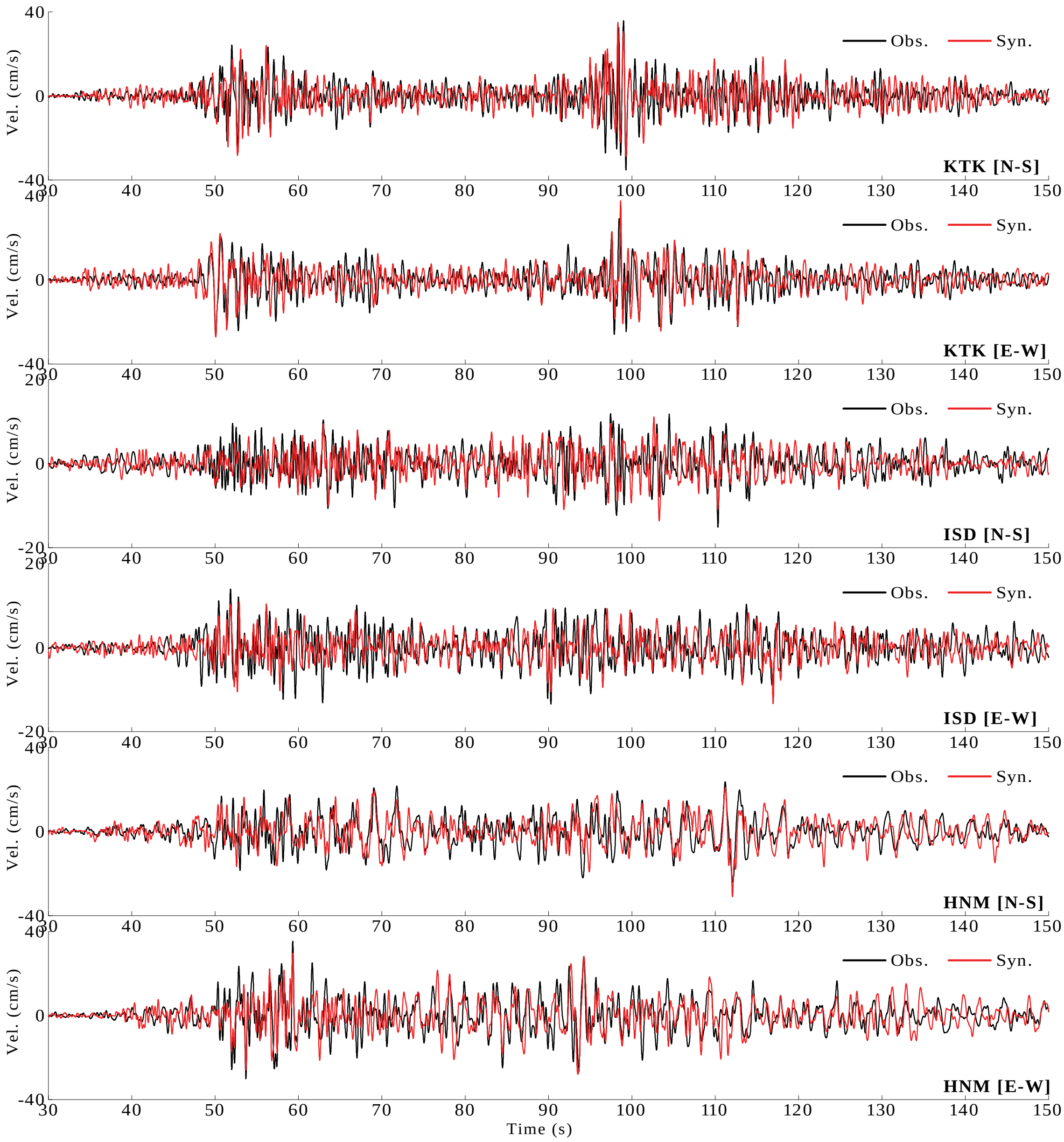

Fig. 10 The observed velocity waveforms and the synthetic velocity waveforms.

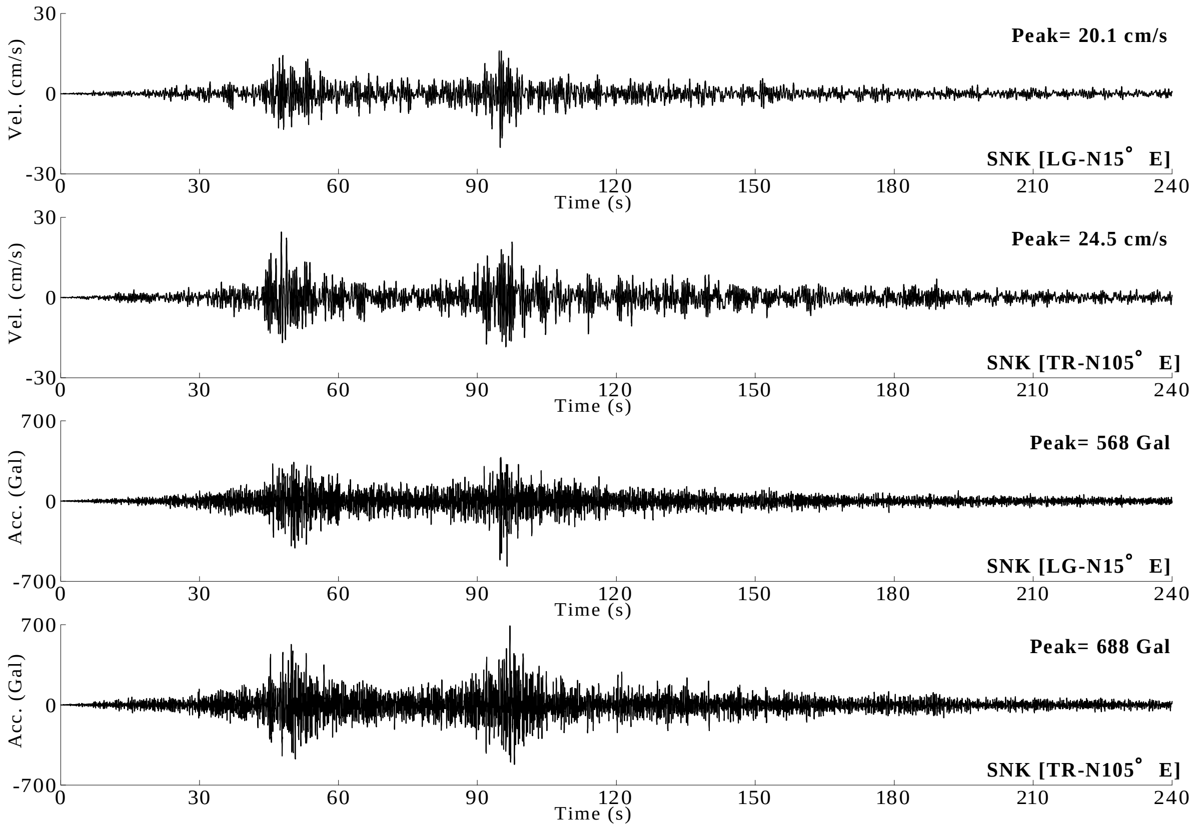

Fig. 11 The estimated ground motion at SNK for the 2011 off the Pacific coast of Tohoku Earthquake

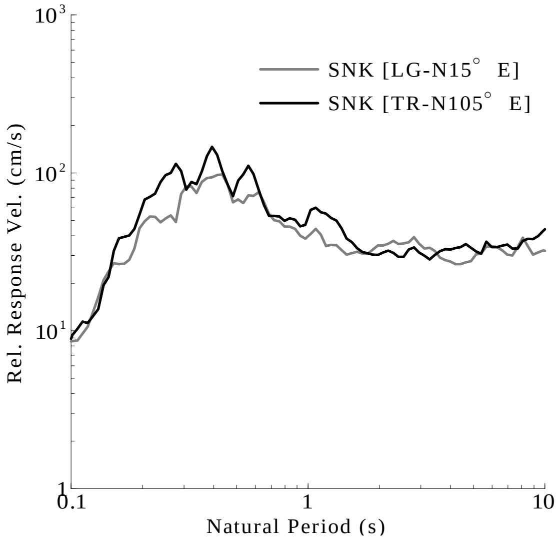

Fig. 12 The relative velocity response spectra

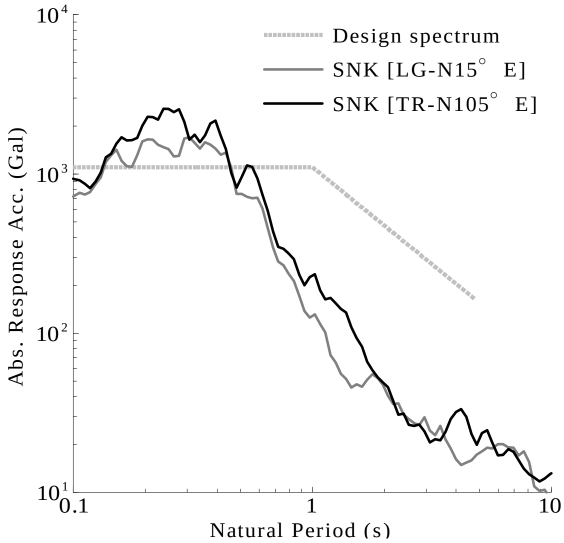

Fig. 13 The absolute acceleration response spectra

Pacific coast of Tohoku Earthquake, especially when contributions from two or more subevents are comparable for the site of interest.

In this article, the authors extend the original site effect substitution method and propose a new method that can be applied to ground motions from a multiple-shock event. In the extended method, the waveform at the permanent strong motion station is divided into sections corresponding to each subevent and the original method is applied to each section. The extended method is applied to the 2011 off the Pacific coast of Tohoku Earthquake to confirm its applicability. In terms of velocity waveforms and Fourier amplitude spectra, the agreement between the estimated and the observed ground motions are quite satisfactory. Thus, it is suggested that the extended method is applicable the 2011 off the Pacific coast of Tohoku Earthquake, at least for the target area. As an application of the extended method, it was used to estimate strong ground motions at the site of the elevated bridges of the Tohoku Shinkansen damaged by the 2011 main shock. As a result, it was found that the estimated response spectra exceed the design response spectrum. Future work should include evaluating the amount of errors quantitatively for the extended method as well as for other methods.

ACKNOWLEDGMENTS

We would like to thank the National Research Institute for Earth Science and Disaster Prevention (NIED) for providing strong motion data. We would also like to thank the Japan Meteorological Agency (JMA) and NIED for providing source parameters of the 2011 off the Pacific coast of Tohoku Earthquake (main shock) and aftershocks. This study was carried out as one of the activities of "Joint Reconnaissance Committee on the 2011 Great East Japan Earthquake (Chairperson: Prof. Akira Mano (Tohoku University))". The authors thank the members of the committee for valuable suggestions.

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