# ESTIMATION OF BASEMENT GROUND MOTION LEVELS FOR THE 2023 TURKEY-SYRIA EARTHQUAKE - A STUDY OF THE APPLICABILITY OF GROUND MOTION MODEL -

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## ABSTRACT

Improving the prediction accuracy of ground motions at large-scale and near-source hard rock sites is important for enhancing probabilistic seismic hazard analysis at nuclear power plants. However, there is a limited amount of large-scale, near-source seismic observation data, and the accumulation of data is essential for improving prediction accuracy. In this paper, we estimated the basement rock ground motion at near-source observation sites based on data from the 2023 Turkey-Syria earthquake (Mw7.8) and compared it with Ground Motion Model (GMM). We constructed a subsurface structural model from the surface to basement rock by referencing a previous study and estimated the basement ground motion based on the diffuse field concept of Nagashima and Kawase (2022). The basement ground motions show a reduced level of ground motion compared to surface observation records. In addition, the basement ground motions and GMM by Morikawa and Fujiwara (2013) were generally consistent within the range of variability, suggesting that GMM by Morikawa and Fujiwara (2013)may allow for reasonably accurate strong ground motion evaluation even when applied outside the extrapolation range of its dataset.

## 1. INTRODUCTION

In probabilistic seismic hazard analysis (PSHA) for nuclear power plants, Ground Motion Models (GMMs) that evaluate average seismic intensity using a small number of parameters, such as magnitude, distance, and ground conditions, are widely used. Since a GMM is an empirical equation constructed based on the observation records of past earthquakes, it can predict strong motion with a certain degree of accuracy within the range of the dataset of the observation records used to construct the model. However, applying a GMM outside the range of the dataset is basically an extrapolation, so careful consideration is required regarding applicability.

In the wake of the accident at the Fukushima Daiichi Nuclear Power Plant in 2011, the seismic sources considered in PSHA have become more diverse and large-scale, and the importance of accurately predicting strong ground motion in large-scale and near-source areas has increased. However, there are still very few large-scale and near-source earthquake observation records, and it is difficult to evaluate them empirically using GMMs. For this reason, in practical PSHA work, it is common to extrapolate from a GMM, but the applicability of the extrapolation range of GMMs and the degree to which strong seismic motion near a seismic source varies aleatory have not been fully elucidated. In particular, it is known that seismic motion during an earthquake varies greatly depending on the ground conditions at the observation point, and even for the same earthquake and the same distance, the seismic motion level will vary even more due to local ground amplification on the ground surface.

The Shikoku Electric Power Company and the Nuclear Risk Research Center of the Central Research Institute of the electric power industry implemented the Ikata SSHAC (Senior Seismic Hazard Analysis Committee) Project to conduct the first PSHA using SSHAC Level 3 in Japan as a voluntary initiative to improve the safety of the Ikata Power Station Unit 3 located in northwestern Shikoku (Fujiwara et al., 2024). For the Ikata SSHAC Project, M9-class large-scale earthquakes, such as the Nankai Trough Megathrust Earthquakes, as well as earthquakes with sources located near the site, such as those in the Median Tectonic Line Active Fault Zone, were assumed and used to evaluate ground motions by using GMMs. With regard to the application of GMMs to M9-class earthquakes, ground motion levels at individual sites peak out even when subjected to large-magnitude earthquakes, and GMMs that consider this effect have been proposed. However, some GMMs are constructed as ground motion levels increase with magnitude, M9-class earthquakes are beyond the range of applications of that GMMs. Hence, there are still issues with the accuracy of their predictions.

In order to improve the accuracy of PSHA at nuclear power plants, it is important to understand the characteristics of seismic motion near the seismic source of large-scale earthquakes, as well as to understand the stable seismic motion level after removing the local amplification of the ground surface at the observation point. In this context, an earthquake with a moment magnitude (Mw) of 7.8 occurred on the East Anatolian Fault in southern Turkey, and many observation records were obtained near the seismic source. In addition, in previous studies, other information was obtained about the ground amplification characteristics of the observation points.

Therefore, in this study, the basement ground motions of the Mw 7.8 main shock were estimated based on the diffuse field concept, and the seismic motion characteristics of the large-scale and near-source areas were investigated, as well as the applicability of the GMM to the range of extrapolation of the dataset.

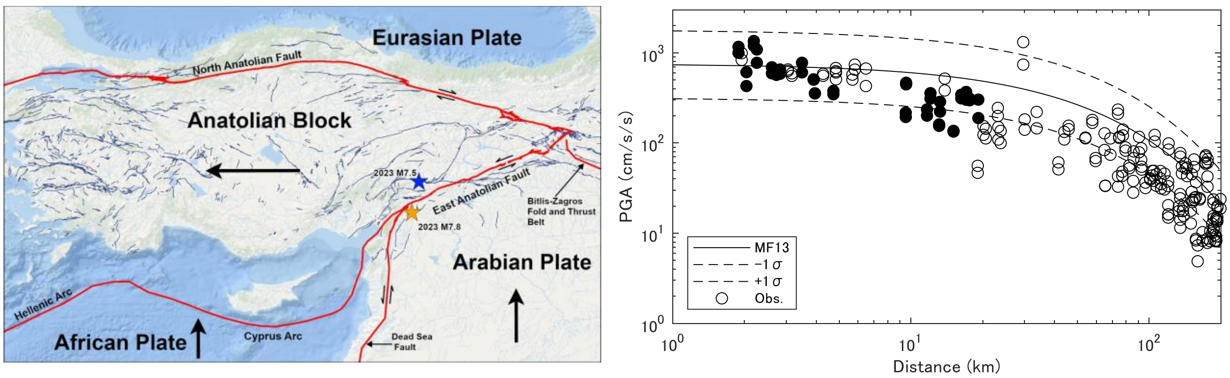
## 2. COLLECTION OF STRONG MOTION OBSERVATION RECORDS

The main shock of the 2023 Turkey-Syria earthquake was a Mw 7.8 earthquake with a depth of 10 km and a left-lateral fault rupture. Many strong-motion observation records were obtained, including those near the seismic source, and they are being organized and made public by the Disaster and Emergency Management Presidency of the Turkish Ministry of Interior (AFAD). In this study, we used AFAD's observation records and visually checked the waveforms and response spectra of the records, excluding ones that had clear defects, such as short recording times and missing main shock parts. The attenuation characteristics of the peak ground acceleration (PGA) of the main shock records collected are shown in Figure 1. We compared the results with the those of the GMM for inland crustal earthquakes of Morikawa and Fujiwara (2013) (MF13), and the results are shown in Figure 1. The PGA was generally within the range of the standard deviation of MF13, and the PGA of surface of the observation points (black dots in the figure) for which the basement ground motions were estimated were generally within the average range for distances to the fault of 10 km or less and were slightly smaller than the average for distances to the fault of 10–20 km.

## 3. SUBSURFACE STRUCTURE MODELING

First, we reviewed previous research on the underground structure of the target area and found that the surface ground structure by AFAD, Özmen et al. (2017), and Yamanaka (2023) and the deep ground structure up to the equivalent of the basement rock by Crust2.0 (Bassin et al., 2000) have been made public. We referred to these previous studies to construct a subsurface structure model. We focused on 19 of the strong-motion records collected in Section 2 (excluding some of the Antakya observation points that may have been subject to local ground amplification) that were within 20 km of the nearest fault and for which the subsurface structure model had been evaluated in previous studies. Figure 2 shows the source fault model of the main shock, the locations of observation points around the source fault, and the locations of observation points for estimating the basement ground motions. The estimation of the basement ground motions based on the diffuse field concept requires a P-wave velocity structure model (Vp model) for the layer shallower than the basement rock. In this study, the models for the layer thickness, Vp, density (ρ), and ground attenuation (Qs and Qp) were set using the following procedure.

1) For the 3123 locations for which the S-wave velocity structure model (Vs model) by Yamanaka (2023) was obtained, the top depth of 360 m for Vs = 2200 m/s in Yamanaka (2023) was assumed to be the top depth of the hard sediments in Crust 2.0, and the layers below the hard sediments were connected.
2) For other locations, where the Vp model was constructed by AFAD, the AFAD model was used for the upper 100 m of the surface layer, the soft sediments and the hard sediments in Crust 2.0 for each observation point were connected for the layers below.
3) For locations where there were no survey results from Yamanaka (2023) or AFAD, Vs model by Özmen et al. (2017) was used for the upper 100 m of the surfade layer, the soft sediments and the hard sediments in Crust 2.0 for each observation point were connected for the layers below.




(a) The epicenter of the 2023 Turkey-Syria earthquake (b) The attenuation characteristics of the PGA

Figure 1. The epicenter (the orange star of the left figure) and attenuation characteristics of PGA (peak ground acceleration of NS and EW direction, the right figure) for the 2023 Turkey-Syria earthquake. The black dots indicate observation points where the basement ground motions were estimated, and MF13 was calculated based on the average ground conditions of all observation points (490 m/s).

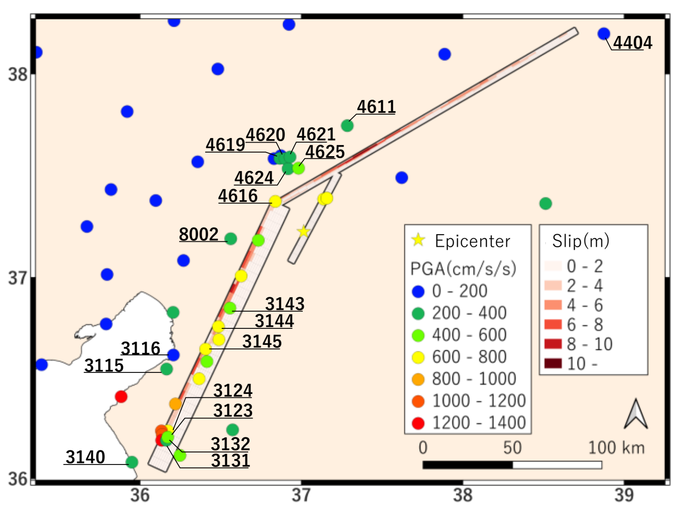



Figure 2. Observation points where the basement ground motions were estimated.
(The rectangular boxes are source fault model and amount of slip from USGS (2023)).

4) If the physical properties required for constructing the Vp model were not available in previous studies, they were set based on the Vp–Vs relationship of Nagashima and Kawase (2019), the $\rho$–Vp relationship of Gardner et al. (1974), the Qs–Vs relationship of the Headquarters for Earthquake Research Promotion (2020), and the Qp–Qs relationship of Todo et al. (1995).

In addition, whereas AFAD, Özmen et al. (2017) and Yamanaka (2023) were constructed from surveys specific to the observation points, Crust 2.0 was a low-resolution model with a resolution of 2 degrees in latitude and longitude. Therefore, we constructed the model by respecting the values of the surface model when Vp values differed at the connection between the surface model and Crust 2.0 (i.e., by changing the Vp and layer thickness values of Crust 2.0). In addition, for the observation points that were close to the installation location of the 3123 points for which the parameters up to the basement rock have been evaluated by Yamanaka (2023) (3124, 3131 and 3132; all of which use the AFAD surface model), the upper depth of the hard sediments in Crust 2.0 was adjusted to the upper depth of Vs = 2200 m/s in Yamanaka (2023) under the assumption that the deep structure does not change significantly.

## 4. ESTIMATION OF BASEMENT GROUND MOTIONS BASED ON THE DIFFUSE FIELD CONCEPT

### *Evaluation Methodology*

Nagashima and Kawase (2022) proposed a method for estimating the horizontal basement wave and nonlinear (equivalent linear) site amplification characteristics during strong ground motion, based on the diffuse field concept, by assuming linearity of the vertical site amplification characteristics and by expressing the horizontal ground amplification characteristics as shown in Equation (1).

$$|TF_{horizontal}(f)| = \frac{H(f)}{V(f)} \times \sqrt{\frac{\beta}{\alpha}} \times |TF_{vertical}(f)| \,, \tag{1}$$

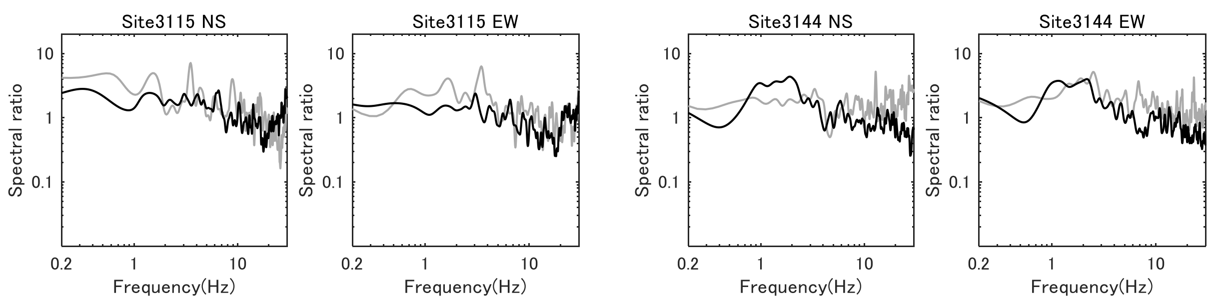
where $H$ and $V$ are the horizontal and vertical spectral amplitudes observed at the surface, $f$ is the frequency, $\alpha$ and $\beta$ are the Vp and Vs of the basement rock, and $|TF|$ is the absolute value of the transfer function from the basement rock to the ground surface. Nagashima and Kawase (2022) confirmed the validity of this theory using multiple observation records, and they stated that if it is possible to assume that a diffuse wave field is established by waves that are scattered in the crust and incident from various directions by using waves that include not only the S-wave but also the coda wave, then the diffuse field concept can be applied to a single seismic wave. In addition, the seismic waves used to evaluate the horizontal-to-vertical spectral ratio (H/V) is based on a 40-s window from the arrival of the S wave, but sometimes the diffusive wave field state is not achieved, as evidenced by the clear appearance of the effects of source radiation characteristics. Nagashima and Kawase (2022) therefore attempted to estimate the basement wave based on the assumption that the diffusive wave field is established if the record is shifted slightly towards the coda from the direct S wave and that it has the same level of nonlinearity as the direct S wave, and they were able to confirm its validity.

It was assumed that the ground response would be nonlinear at many observation points for the 2023 Turkey-Syria earthquake, but nonlinear characteristics were not proposed in the previous studies discussed in Section 3. Therefore, in this study, we used the method of Nagashima and Kawase (2022), which can empirically consider the nonlinear behavior of the ground based on H/V to estimate basement ground motions using the records of observation points near the seismic source of the 2023 Turkey-Syria earthquake and the Vp model. Here, we evaluated the basement surface at the top of the hard sediment layer (Vs = 2100 m/s), bearing in mind that Vs corresponding to the base surface is set in the hard sediments of Crust 2.0 and that the evaluated basement ground motions are compared with the predicted value of Vs30 = 2000 m/s by MF13.

***Evaluation of mainshock H/V and estimation of basement ground motions***

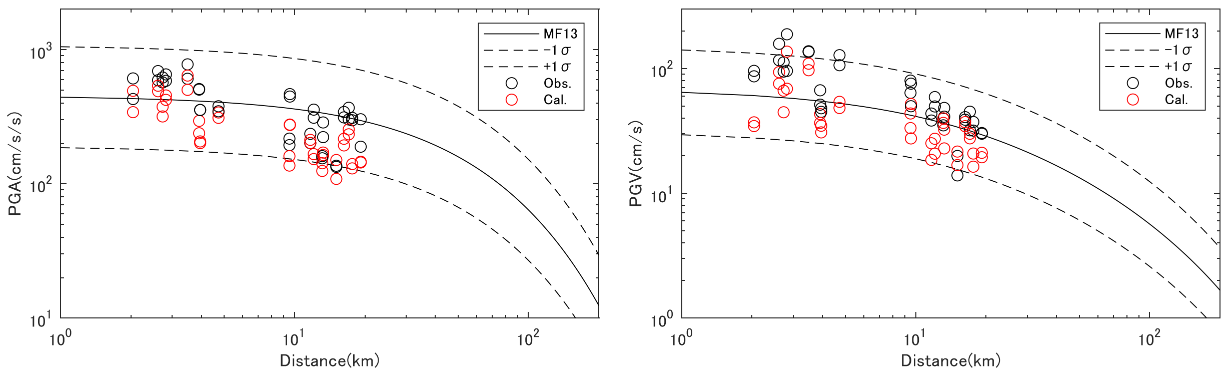
The H/V values for the main shock were evaluated for the 19 target locations. The main shock involved the activity of a long fault, and it took more than 40-s for all the faults to rupture. In some cases, the maximum amplitude was recorded after 40-s had elapsed since the arrival of the S wave. In such cases, it is possible that the ground properties, which had become nonlinear because of the large amplitude, could not be reflected in the 40-s analysis section. For this reason, some of the evaluation conditions were changed, such as evaluating H/V in the 40-s analysis section so that it included at least 10 s after the arrival of the maximum seismic motion, but the basic method was based on that of Nagashima and Kawase (2022). After that, a cosine taper was applied to the 1-s section before and after the analysis section, a Fourier amplitude spectrum was obtained by fast Fourier transform, and the H/V was calculated after smoothing it with a Parzen window of 0.5 Hz. An example of the evaluated H/V of the main shock is shown in Figure 3, along with a comparison with the H/V of a weak seismic record that was considered to have a small nonlinear effect. The weak seismic records were selected from among the records of earthquakes that occurred before the main shock and had a PGA of 100 cm/s$^2$ or less; the record with the largest PGA from this group was selected. The fact that the main shock H/V at the 3144 locations showed a decrease in amplitude at high frequencies compared to the weak seismic H/V was probably due to the influence of nonlinear behavior of the shallow ground.

Next, we used the subsurface structure model constructed in Section 3 to calculate the theoretical amplification ratio of vertical motion from the ground surface to the basement surface using a one-dimensional wave equation and then used the main shock H/V to calculate the ground amplification ratio of horizontal motion using Equation (1). The Fourier amplitude spectrum of the basement surface obtained by dividing the observed record at the ground surface by the ground amplification factor for horizontal motion and the phase of the observed record were combined to evaluate the seismic motion at the basement surface (Vs = 2100 m/s). The attenuation characteristics of the basement ground motion (PGA and PGV) at all observation points are shown in Figure 4. Examples of the observation record, estimated ground amplification factors from the basement surface, basement ground motion, and basement response spectra are shown in Figure 5. The estimated PGA and PGV of basement ground motions were almost within the range of variation of MF13 (Vs30 = 2000 m/s), and it was confirmed that the seismic motion level was generally reduced compared to the surface observation records.



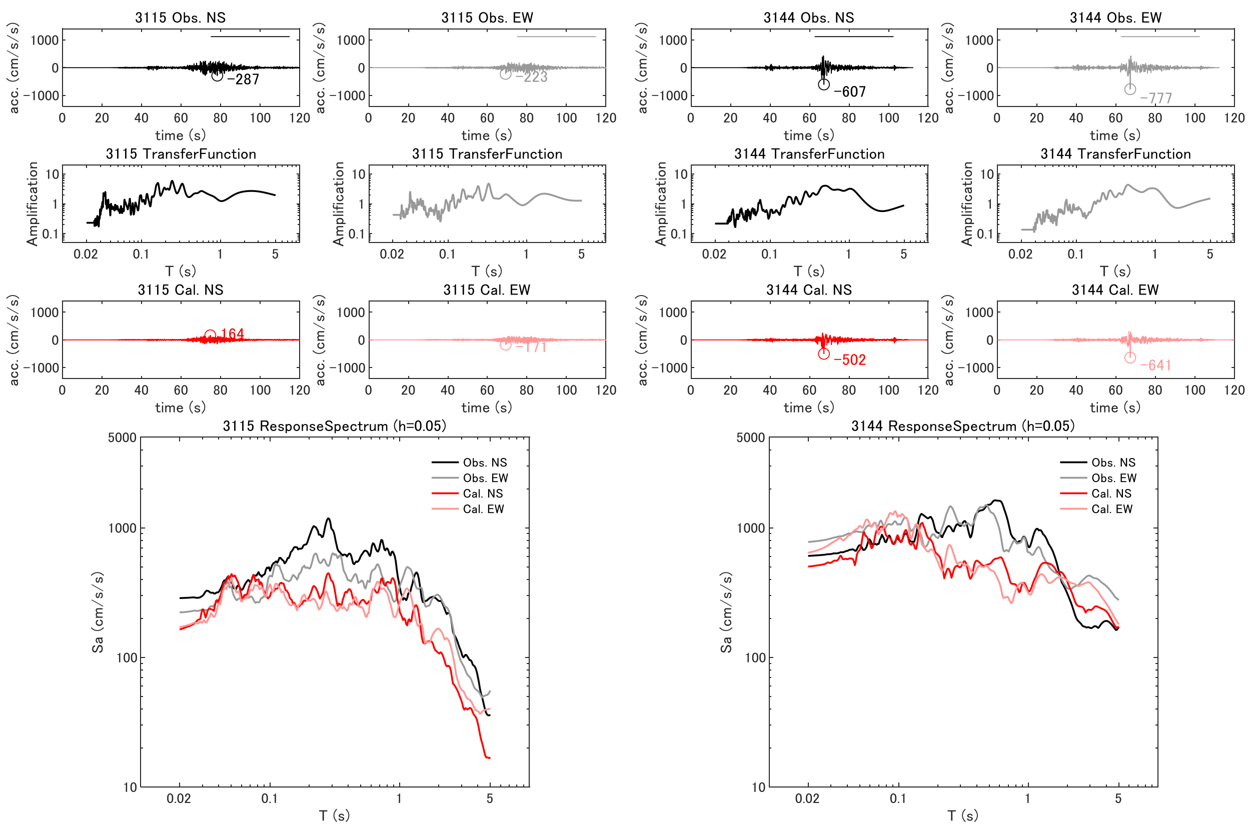

(a) Site 3115 (b) Site 3144

Figure 3. Observed H/V (black: main shock record; gray: same location, weak seismic record).




(a) PGA (b) PGV

Figure 4. Attenuation characteristics of observation records (Obs.) and basement ground motions (Cal.). MF13 was calculated with Vs30 = 2000 m/s.




(a) Site 3115 (b) Site 3144

Figure 5. Results of estimating the basement ground motion based on the diffused field concept. Obs. indicates the surface observation record, and Cal. indicates the estimated basement ground motion. The section of the line at the top of the observation record is the analysis section of H/V, and the transfer function outside the effective frequency range set with reference to AFAD is extrapolated from the values at the ends. The shortest distance to the fault is 13.3 km for station 3115 and 3.5 km for station 3144.

## 5. APPLICABILITY OF THE GROUND MOTION MODEL

As mentioned in the introduction, in order to improve the accuracy of strong motion prediction for future earthquake-resistant design, it is important to understand the characteristics of large-scale seismic motion near the seismic source. In particular, when considering earthquake-resistant measures for buildings, it is necessary to consider the effects on structures with various period characteristics. The Headquarters for Earthquake Research Promotion (2022) has been working on the development of a seismic hazard assessment method for response spectra using MF13, and a preliminary report has been published. The report includes future issues to be addressed, such as improving the prediction accuracy for large-scale earthquakes and for locations very close to the seismic source, as well as improving the prediction accuracy by using basement waves that exclude the amplification effect of the surface layer. The results of this study provide useful data for addressing these issues.

In this section, we considered the applicability of MF13 to large-scale, near-source ground motion by comparing the attenuation characteristics of each period for the basement ground motions estimated in Section 4 and those estimated by MF13 (Vs30 = 2000 m/s). The results of the comparison are shown in Figure 6. Because MF13 evaluates response spectra with a period of 0.05 s or more, the panel shows a period of 0.02 s uses the PGA value for MF13.

The estimated basement ground motions and the results of MF13 generally correspond well in all frequency bands. For observation points with a fault distance of 10–20 km, the values were slightly lower than the MF13 average in the short-period region of about 0.1 s or less, and although the values were generally lower than the average in the region around 1.5–2 s, they were within the range of variation. The MF13 dataset includes the 2007 Noto Peninsula Earthquake and the 2007 Niigata-ken Chuetsu Offshore Earthquake (each with an Mw of about 7.0 and a fault length of about 10 km). The data included records from K-NET Anamizu for the Noto Peninsula Earthquake and at K-NET Kashiwazaki for the Niigata-ken Chuetsu Offshore Earthquake; these showed large amplitudes of more than 200 cm/s at periods of 1 s or more. It is not known whether the period characteristics of seismic motion experienced at such an earthquake scale and short distance to the fault will also occur in earthquakes of a larger scale. It is possible that the seismic motion level estimated by MF13 is larger than the estimated basement ground motions in this study at a period of about 1.5–2 s by applying the characteristics of the MF13, which was optimized using seismic observation records of up to about Mw 7.0, to the extrapolation range. In addition, while the estimated basement ground motions are free-field evaluation values, the MF13 evaluation values were obtained by regression of data from observation points with Vs30 = 2000 m/s. Therefore, the results of MF13 were not strictly free-field values and included the effect of short-period seismic motion being amplified by thin layers near the surface. For observation points with a fault distance of 10–20 km, the difference between the estimated basement ground motions and MF13 in the short-period region of 0.1-s or less may be due to this effect.

As shown above, the basement ground motions of the 2023 Turkey-Syria earthquake and the results of MF13 (Vs30 = 2000 m/s) generally corresponded well within the range of variation, and it has been shown that MF13 has the potential to be used for strong motion evaluation with a certain degree of accuracy even in the extrapolation range of the dataset. However, there were some cases where MF13 produced slightly larger results depending on the period, and it is important to continue to verify whether these characteristics are universal or specific to the 2023 Turkey-Syria earthquake while continuing to accumulate large-scale data near the seismic source.

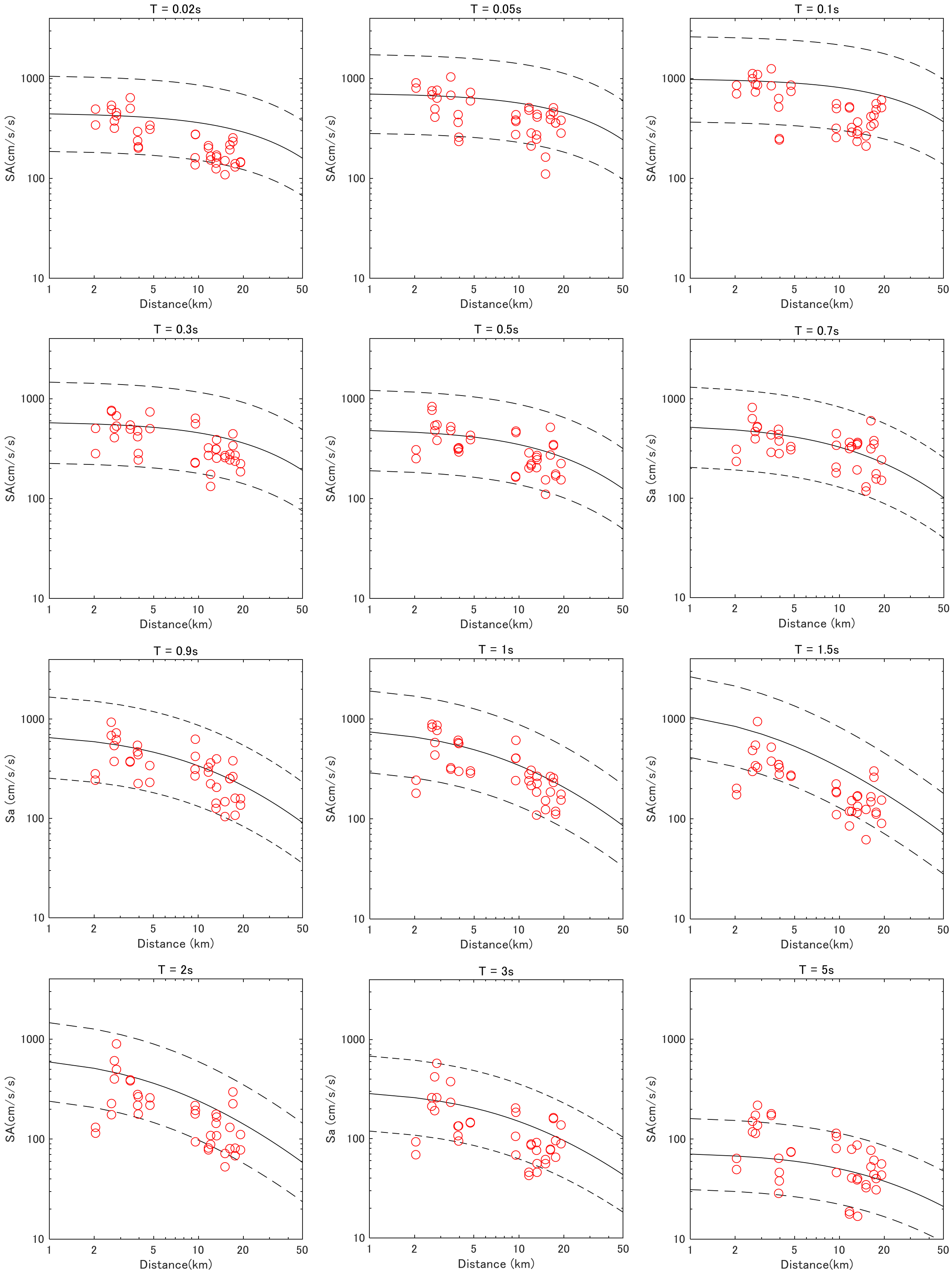



Figure 6. Comparison of the estimated basement ground motions and the response spectrum of MF13 (Vs30 = 2000 m/s). The red circles show the estimated basement ground motions, and the black solid and dotted lines show the average and ±1σ of MF13, respectively.

## 6. CONCLUSION

In this study, in order to understand the characteristics of large-scale seismic motion near a seismic source in areas where there has been a lack of observational data, we estimated the basement ground motions based on the diffuse field concept using the main shock records of the 2023 Turkey-Syria earthquake.

Using a Vp model constructed by referring to previous studies and combining it with the H/V of observation records, we evaluated the transfer function from the basement rock to the ground surface and estimated seismic motion at the basement surface. The estimated PGA and PGV of the basement ground motions were almost within the range of the variation of MF13 (Vs30 = 2000 m/s), and it was confirmed that the basement ground motion levels were generally reduced compared to the surface observation records.

By comparing the attenuation characteristics of the estimated basement ground motions and the results of MF13 (Vs30 = 2000 m/s) for each period, we considered the applicability of MF13 to large-scale basement ground motions near the seismic source. The results of MF13 and the basement ground motions of the 2023 Turkey-Syria earthquake generally corresponded well within the range of variation, and it was shown that MF13 could be used to evaluate strong seismic motion with a certain degree of accuracy even in the extrapolation range of the dataset.

This study shows that the MF13 can be used to accurately evaluate large-scale, near-source seismic motion at hard rock sites, and is a useful knowledge that will lead to improved accuracy in PSHA of nuclear facilities using GMM. However, because this study was based on a single case study of the 2023 Turkey-Syria earthquake, it is important to continue to verify the applicability to the extrapolation range of the dataset while accumulating large-scale data near a seismic source.

## ACKNOWLEDGMENTS

In preparing this report, we used the observation records of AFAD (https://tadas.afad.gov.tr/map), the seismic source fault model of the USGS. The English in this manuscript was carefully corrected by two native-English speaking, professional editors, both with extensive research editing experience.

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