



Full-waveform prediction of high-frequency ground motion at depth from surface recordings in Japan

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Abstract: The earthquake shaking observed on the ground surface differs from the shaking at depth beneath. This applies to observed temporal waveforms and intensity measure types such as PGA, and PGV. Such phenomenon is caused by the near-surface layers of soft rocks and soils that cause amplification and attenuation of seismic waves. The prediction of a possible ground motion at a site of interest is important for earthquake resistance design. Advancements in the prediction of the ground motion at depth are especially important for the design of deep geological disposals, buildings with deep foundations, or for studies of soil-structure interaction. In this contribution, we demonstrate our recently developed method to predict high-frequency ground motion at depth from surface recordings. We make use of a stochastic model formulated in the Fourier domain, which is based on a response of a layered 1D medium to incident body waves. We apply the method to predict borehole waveforms from surface recordings of the 2018 northern Osaka and 2013 Awaji Island earthquakes (Japan). Comparison of predicted and observed acceleration waveforms at four borehole sites show a high level of similarity in the broadband frequency range and well-predicted values of PGA and PGV at depth.

Keywords: broadband waveforms, site effects, KiK-net, PGA, PGV

1. Introduction

The design of structures for earthquake resistance requires an assessment of the local seismic hazard. In the case of structures of special importance, the seismic hazard is evaluated for long return periods and should take into account rock and soil conditions at the construction foundation. These site-specific conditions cause amplification and attenuation of seismic waves and can be approximated by using soil classes (CEN 2004, SIA 2020). Still, the soil classes provide only simplistic insight into the true earthquake site response and are not applicable for important underground structures in the current form. Therefore, there is a need to characterize a possible ground motion at depth for such underground structures (e.g. nuclear waste repositories) or buildings with deep foundations.

The ground-shaking caused by earthquakes can be characterized by the peak ground acceleration (PGA), peak ground velocity (PGV), pseudo-acceleration spectrum (PSA), or by full temporal waveforms (e.g. Archuleta et al. 2003, Zhao et al. 2006, Boore and Atkinson 2008, Edwards and Fäh 2013). The prediction is standardly evaluated on the ground surface, and predictions at depth are rather rare. Recently, Hallo et al. (2022) proposed a novel method to characterize the high-frequency ground motion at depth, which is also suitable for predictions of broadband waveforms in the Fourier domain.

In this contribution, we apply the method by Hallo et al. (2022) to predict the ground motion at depth from surface recordings of two significant crustal earthquakes: the 2018 northern

Osaka M_w 5.6 earthquake (Kato and Ueda 2019, Hallo et al. 2019), and the 2013 Awaji Island M_w 5.8 earthquake (Twayana et al. 2014, Asano et al. 2016, Imanishi et al. 2020). The full-waveform predictions are performed at KiK-net sites equipped with both surface and borehole sensors, which allows direct comparison with empirical data. Then, we evaluate the mutual fit of observed and predicted waveforms, PGA, and PGV at depth.

2. Method

Let us assume a broadband acceleration waveform observed on the ground surface $y_s(t)$, where t denotes time. Its Fourier transformation yields an acceleration spectrum $Y_s(f)$, which can be related to the acceleration spectrum at depth through a surface-borehole transfer function. Following Hallo et al. (2022), a predictive surface-borehole transfer function $\hat{H}(f)$ is evaluated using a stochastic model that is based on an estimate of the local 1D medium. Then, the prediction of the acceleration spectrum at depth $\hat{Y}_B(f)$ is

$$\hat{Y}_B(f) = \frac{Y_s(f)}{\hat{H}(f)} \quad (1)$$

where f denotes frequency. The inverse Fourier transformation of $\hat{Y}_B(f)$ yields the full-waveform prediction of ground motion at depth $\hat{y}_B(t)$. The stochastic model, assumed 1D layered media, and predictive surface-borehole transfer functions are described in detail by Hallo et al. (2022).

3. Application to prediction of ground motion at depth

We apply the method to predict broadband borehole waveforms from earthquake recordings observed on the ground surface. In particular, we use acceleration data from the KiK-net strong-motion monitoring network (Aoi et al. 2011). The predicted waveforms are compared with the transverse horizontal component of ground motion observed in borehole arrays at four selected sites (HYGH04, HYGH10, KYTH03, and KYTH08).

3.1. The 2018 northern Osaka M_w 5.6 earthquake

The 2018 northern Osaka M_w 5.6 (M_{JMA} 6.1) earthquake occurred on 18th June 2018 beneath the Takatsuki city (Osaka-fu, Japan). This earthquake was caused by joint movements on strike-slip and reverse crustal faults (Kato and Ueda 2019, Hallo et al. 2019). The comparison of predicted and observed ground motion at depth is shown in Figs 1–4 and summarized in Table 1. The KYTH08 site (Fig. 1) is located in epicentre distance of 21 km with the borehole sensor deployed at 704 m depth. The prediction of high-frequency P-wave amplitude is underestimated at the HYGH04 site (Fig. 2) as the method is intended for S-waves. Both HYGH10 and KYTH03 sites (Figs 3 and 4, respectively) exhibit good mutual fit in a wide frequency range. Also, note a high level of similarity of observed and predicted PGA and PGV at depth shown in Table 1.

Table 1. Application to the 2018 northern Osaka earthquake

Station name	Epicentre distance (km)	Borehole depth (m)	Surface		Borehole			
			PGA (cm/s ²)	PGV (cm/s)	PGA (cm/s ²)		PGV (cm/s)	
					Observed	Predicted	Observed	Predicted
KYTH08	21	704	142.6	4.35	33.5	28.2	2.97	1.30
HYGH04	40	100	63.8	2.30	16.3	16.3	1.50	1.69
HYGH10	75	100	29.6	1.63	9.1	7.2	0.46	0.57
KYTH03	69	300	15.9	0.60	3.5	3.0	0.35	0.37

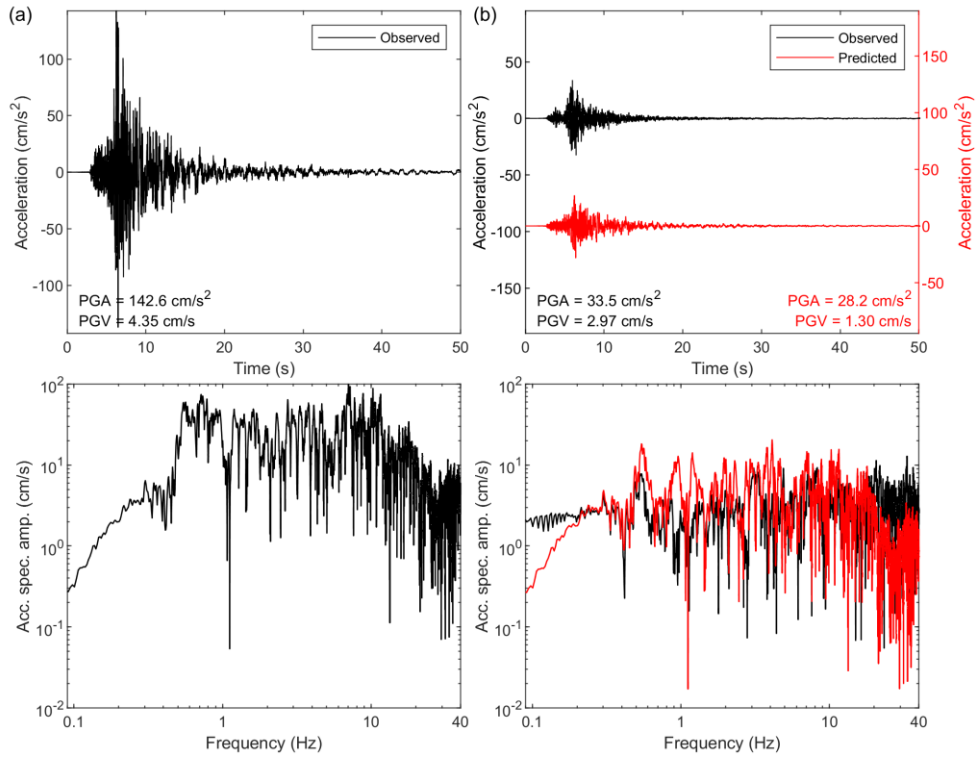


Fig. 1 - The 2018 northern Osaka earthquake: Prediction of the ground motion at depth at the KYTH08 site. (a) Transverse component of the horizontal ground motion observed on the surface. (b) Observed (black) and predicted (red) horizontal ground motion in the borehole at 704 m depth.

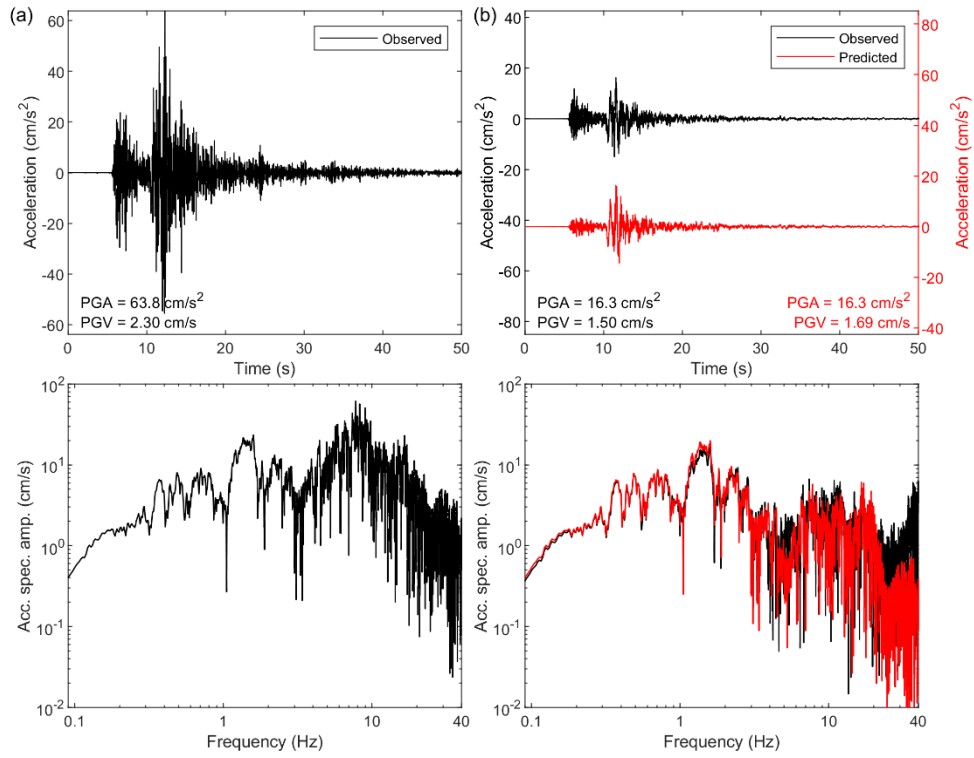


Fig. 2 - The 2018 northern Osaka earthquake: Prediction of the ground motion at depth at the HYGH04 site. (a) Transverse component of the horizontal ground motion observed on the surface. (b) Observed (black) and predicted (red) horizontal ground motion in the borehole at 100 m depth.

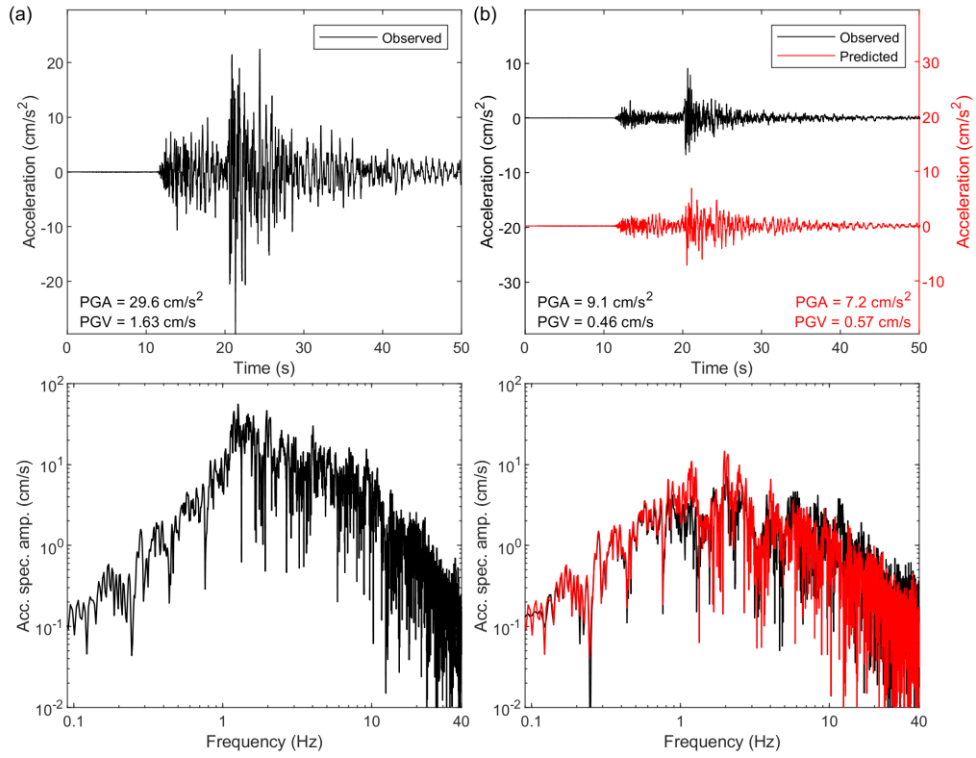


Fig. 3 - The 2018 northern Osaka earthquake: Prediction of the ground motion at depth at the HYGH10 site. (a) Transverse component of the horizontal ground motion observed on the surface. (b) Observed (black) and predicted (red) horizontal ground motion in the borehole at 100 m depth.

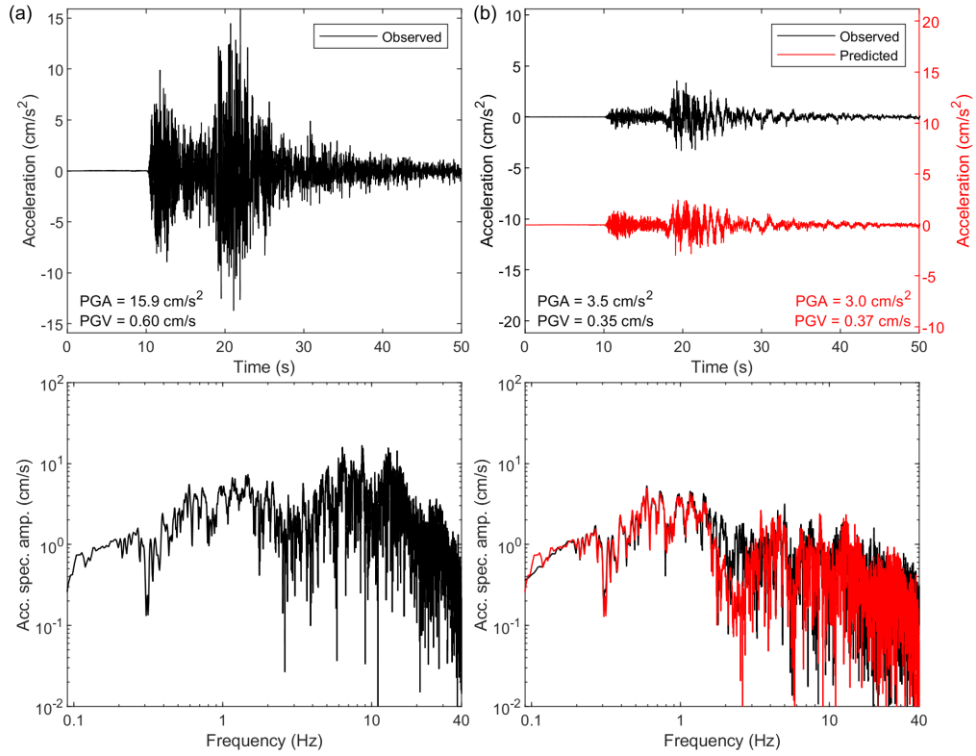


Fig. 4 - The 2018 northern Osaka earthquake: Prediction of the ground motion at depth at the KYTH03 site. (a) Transverse component of the horizontal ground motion observed on the surface. (b) Observed (black) and predicted (red) horizontal ground motion in the borehole at 300 m depth.

3.2. The 2013 Awaji Island M_w 5.8 earthquake

The 2013 Awaji Island M_w 5.8 (M_{JMA} 6.3) earthquake occurred on 13th April 2013 beneath the Awaji-shima (Hyogo-ken, Japan). This earthquake caused local damage (Twayana et al. 2014), it excited significant low-frequency (<0.5 Hz) ground motion in the Osaka sedimentary basin (Asano et al. 2016), and it was caused by shear movements on a reverse crustal fault (Imanishi et al. 2020). The comparison of predicted and observed ground motion at depth at selected KiK-net sites is shown in Figs 5–7 and summarized in Table 2. The spectral shape and overall characteristics at depth are well predicted at the HYGH10 site (Fig. 5). Both KYTH03 and KYTH08 sites (Figs 6 and 7, respectively) exhibit a good fit of prediction with observed data despite the epicentre distance being larger than 100 km. Finally, note a high level of similarity of observed and predicted PGA and PGV at depth shown in Table 2.

Table 2. Application to the 2013 Awaji Island earthquake

Station name	Epicentre distance (km)	Borehole depth (m)	Surface		Borehole			
			PGA (cm/s^2)	PGV (cm/s)	PGA (cm/s^2)		PGV (cm/s)	
					Observed	Predicted	Observed	Predicted
HYGH10	44	100	40.7	2.52	10.3	8.4	0.53	0.73
KYTH03	103	300	22.6	0.59	4.6	4.9	0.30	0.27
KYTH08	105	704	14.7	0.53	1.7	2.0	0.11	0.12

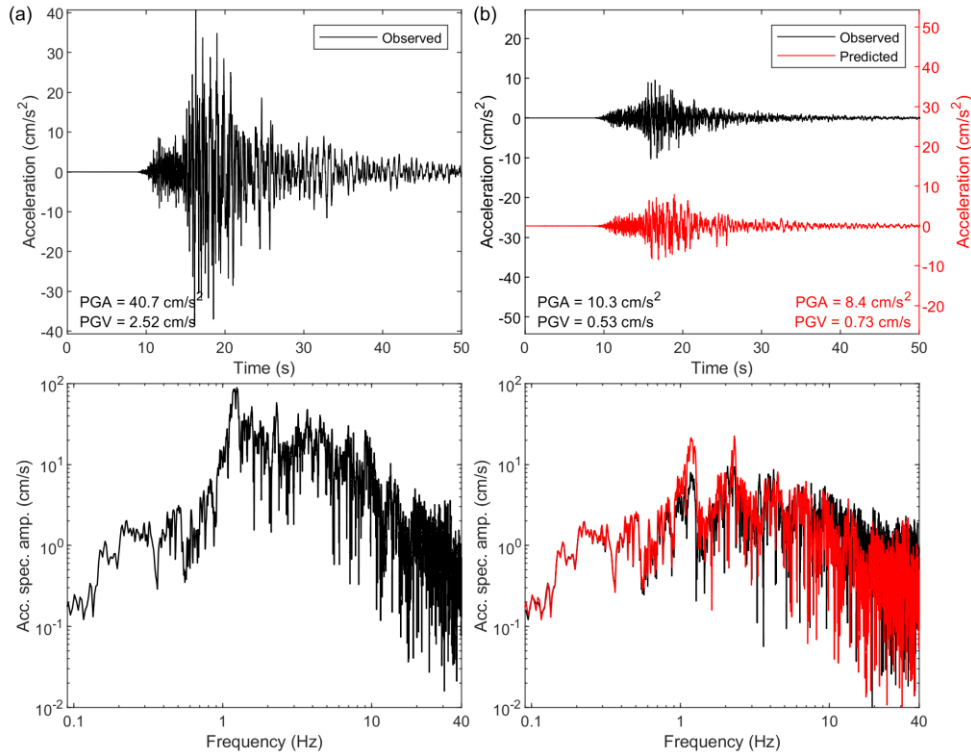


Fig. 5 - The 2013 Awaji Island earthquake: Prediction of the ground motion at depth at the HYGH10 site. (a) Transverse component of the horizontal ground motion observed on the surface. (b) Observed (black) and predicted (red) horizontal ground motion in the borehole at 100 m depth.

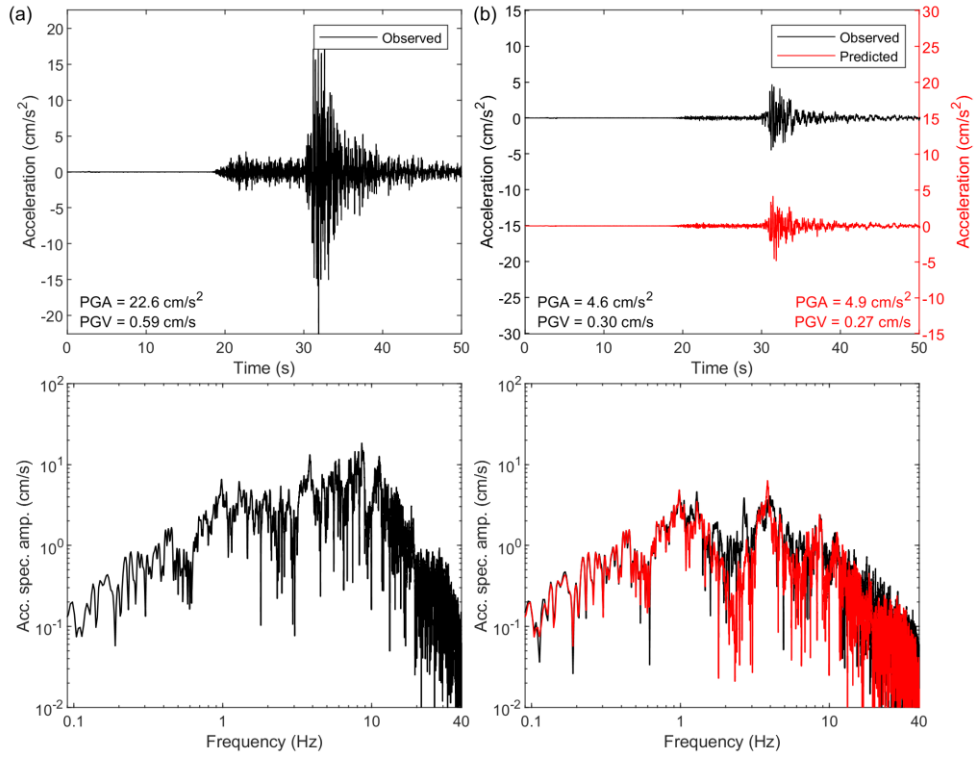


Fig. 6 - The 2013 Awaji Island earthquake: Prediction of the ground motion at depth at the KYTH03 site. (a) Transverse component of the horizontal ground motion observed on the surface. (b) Observed (black) and predicted (red) horizontal ground motion in the borehole at 300 m depth.

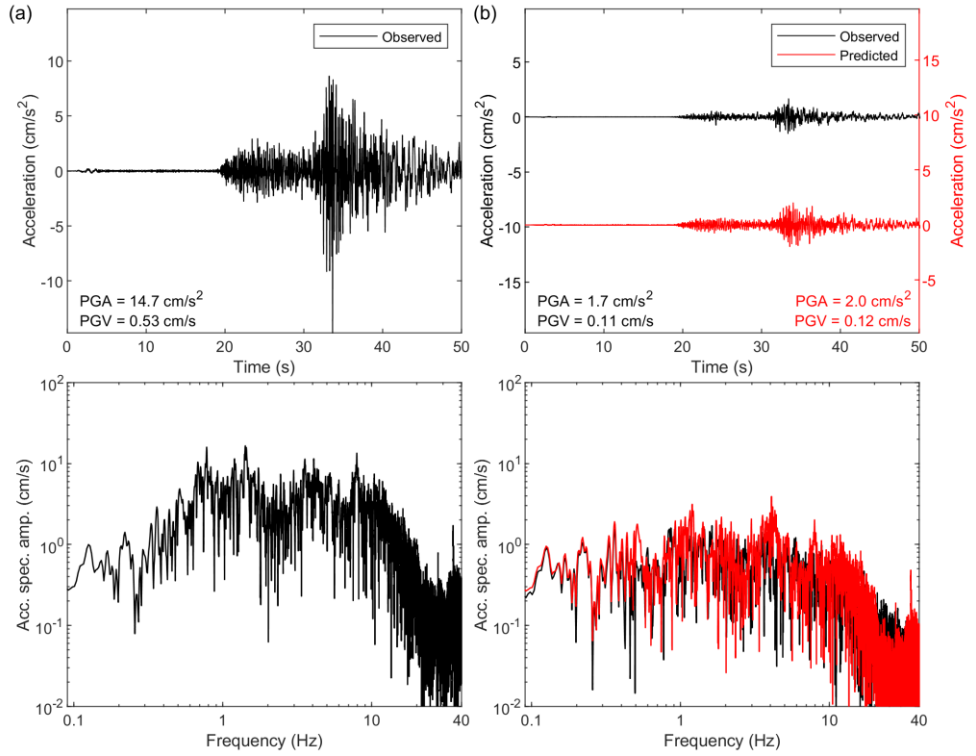


Fig. 7 - The 2013 Awaji Island earthquake: Prediction of the ground motion at depth at the KYTH08 site. (a) Transverse component of the horizontal ground motion observed on the surface. (b) Observed (black) and predicted (red) horizontal ground motion in the borehole at 704 m depth.

3.3. Misfit of predicted and empirical spectra at depth

Let us denote the empirical acceleration waveform observed at depth as $y_B(t)$ and its acceleration spectrum as $Y_B(f)$. The observed $Y_B(f)$ and predicted $\hat{Y}_B(f)$ spectra at depth are very similar but not identical. Therefore, we can compute misfits of amplitude spectra for multiple earthquakes in order to evaluate systematic errors of the prediction method. The normalized misfit can be expressed as

$$\text{Misfit}(f) = \frac{|Y_B(f)| - |\hat{Y}_B(f)|}{\max(|y_B(t)|)} \cdot 100\% \quad (2)$$

where $\max(|y_B(t)|)$ is the PGA observed at a depth. In Fig. 8, the resultant misfit functions are shown for both northern Osaka (red) and Awaji Island (blue) earthquakes. The prediction at the HYGH10 site seems to have a systematic discrepancy at about 1.1 and 2.2 Hz (Fig. 8a). On the other hand, predictions at KYTH03 and KYTH08 sites do not show systematic misfit features for multiple earthquakes (see Fig. 8b and 8c). The latter might imply that we can see unsystematic inter-event variations of the observed ground motions.

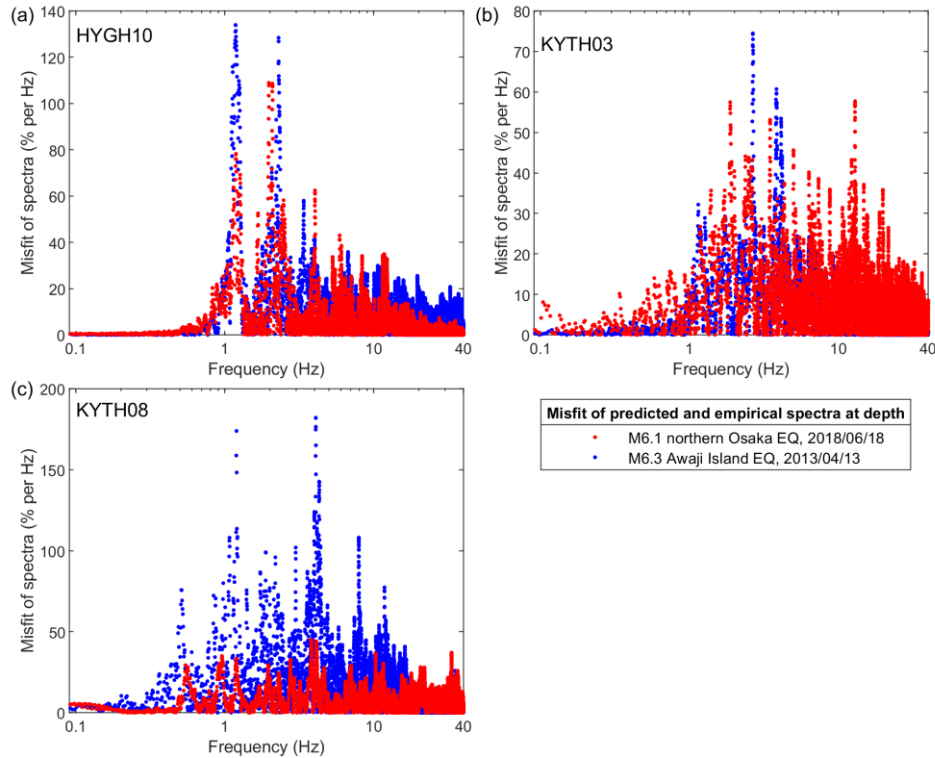


Fig. 8 - Misfit of predicted and empirical spectra at depth for (a) HYGH10, (b) KYTH03, and (c) KYTH08 sites. The misfit is calculated by equation (2) for both northern Osaka and Awaji Island earthquakes.

4. Conclusions

In this contribution, we demonstrate the performance of our recent method to predict high-frequency ground motion at depth from surface recordings. The method introduced by Hallo et al. (2022) is applied to predict borehole waveforms of the 2018 northern Osaka $M_w 5.6$ earthquake and the 2013 Awaji Island $M_w 5.8$ earthquake (Kansai region, Japan). A comparison of predicted and observed acceleration waveforms at four borehole KiK-net sites shows a high level of similarity in the 0.1–40 Hz frequency range. Further, predicted values of PGA and PGV are satisfactorily close to observed ones in most of the investigated cases.

To conclude, the method can be applied to earthquake resistance design purposes, e.g., the design of deep geological disposals, buildings with deep foundations, or for studies of soil-structure interaction.

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