

ON A STOCHASTIC MODEL TO CHARACTERIZE HIGH-FREQUENCY GROUND MOTION AT DEPTH

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ABSTRACT

The goal of this contribution is to develop a physical-based approach to construct site-specific depth-to-surface amplification and duration stochastic models. We first derive a set of 1D velocity profiles considering various possible (physical) effects of the near-surface geology on ground motions. These velocity models are used for the computation of an ensemble of the depth-to-surface SH-wave transfer functions. Then, the ensemble of such transfer functions is used for the construction of a stochastic model by means of Gaussian statistics in the spectral density (amplification term) and the envelope delay (temporal term). We demonstrate that such a stochastic model can be used for the prediction of the depth-to-surface amplification, and we compare the prediction with an empirical depth-to-surface amplification as retrieved from borehole installations of the Japanese KiK-net network.

Keywords: stochastic, ground motion at depth, spectral density, duration, KiK-net

INTRODUCTION

Advancements in the site-specific high-frequency ($>1\text{Hz}$) attenuation and amplification are essential for improving the accuracy of the ground-motion prediction on a local scale. The site-specific attenuation observed on the surface is typically described by parameter kappa (κ_0). It can be evaluated empirically, however predictions by using v_{s30} adjustments on classical ground-motion prediction equations are subject to high epistemic uncertainties (Bard et al., 2020). This gives rise to a need for separation of the path- (observed at depth) and site- (observed on surface) terms of the attenuation. The empirical site response may be estimated by the comparison of ground-motions with a reference outcrop rock site nearby; nevertheless, the outcrop site can be fractured and weathered that alters the ground-motion (Steidl et al., 1996). Hence, the usage of ground-motion observed at depth should be preferred. Moreover, there is a need to characterize ground motion at depth in the seismic hazard assessment of deep geological disposals (e.g., nuclear waste repositories), with a particular need to characterize high-frequency ground motion for seismic design purposes. This highlights the importance of the advancements to predict the high-frequency ground motion at depth.

For simplicity, it is common to assume a linear site response of a one-dimensional (1D) medium of horizontal homogeneous layers. Then assuming body waves propagating sub-vertically through a 1D layered medium, the horizontally polarized ground-motion on the surface may be related to the ground-motion at depth using a site-specific depth-to-surface SH-wave transfer function (e.g., Bonilla et al., 2002). Such a function can be evaluated numerically (Thomson, 1950); however, transfer functions computed in a 1D velocity model contain artificial 1D resonance peaks (e.g., Tao and Rathje, 2020), rarely observed in real high-frequency data due to the complexity of near-surface geology. Hence, we propose a stochastic depth-to-surface model that takes these possible random effects of the 1D structure into account. The additional variability introduced by the stochastic model is rather advantageous, and it will have just a minor effect on the record-to-record variability (e.g., Bazzurro and Cornell, 2004).

CONSTRUCTION OF THE MODEL

The construction of our depth-to-surface stochastic model consists of three steps as follows:

Perturbed velocity models

First, we prepare a set of 1D velocity profiles considering various possible random effects of the near-surface geology. The assumed effects are random but based on physical principles and prior knowledge of the particular site. In particular, we use random perturbation drawn from a Gaussian distribution of the shear modulus, mass density, medium damping, and depth of interfaces, centered on the reference 1D velocity model. The S-wave velocity v_s is related to the mass density ρ and shear modulus μ by

$$v_s = \sqrt{\frac{\mu}{\rho}} \quad (1)$$

And the medium damping ξ is related to the quality factor Q_s by

$$\xi = \frac{1}{2Q_s} \quad (2)$$

Following Olsen et al. (2003), we can approximate the S-wave quality factor to be one-tenth of the S-wave velocity. The random models are then drawn from the Gaussian distribution having a standard deviation of 15% of the reference model value. Alternatively, we might use a set of 1D velocity models resulting from a Bayesian inversion (e.g., Hallo et al., 2021), or use various strength of random perturbations for various layers. As an example in Fig. 1, we show perturbed velocity models at the KSRH10 site of the KiK-net network (Aoi et al., 2011; NIED, 2019; Okada et al., 2004) having a borehole array installation. The density in Fig. 1b is only an estimate, as not measured at this site.

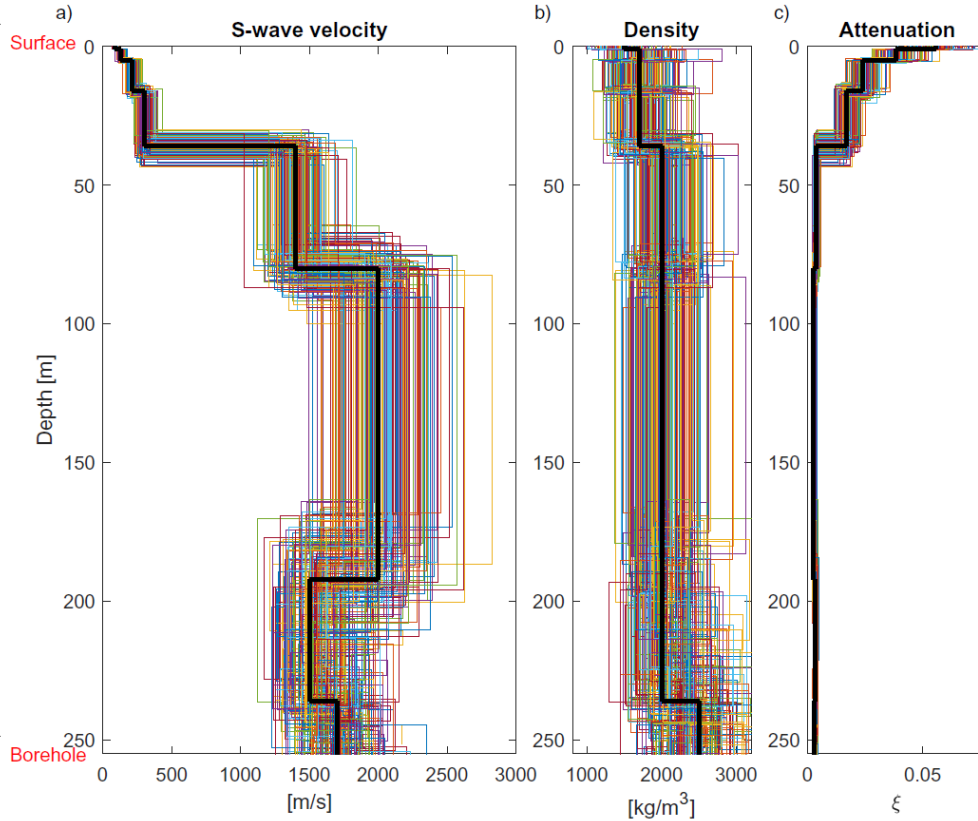


Figure 1. Perturbed velocity models at the KSRH10 site (Hokkaido, Japan). The reference S-wave velocity model (NIED, 2019) is shown by the black solid line (Fig. 1a). Borehole installation at this site consists of surface (0 m) and downhole (255 m depth) receivers.

Ensemble of transfer functions

According to the theory, the incidence plane body wave at a bottom depth of a layered structure propagates vertically as an upward wave to the surface. Then, it is reflected due to the free-surface boundary and continues as a downward wave. As result, the ground motion at the surface is amplified by a factor of two, and the ground motion at depth is composed of upward and downward plane waves. The spectrum ratio at the ground surface and bottom depth can be expressed as a complex transfer function $H(f)$ by

$$H(f) = \frac{2A_S(f)}{A_D(f) + B_D(f)} \quad (3)$$

where $A_S(f)$ is Fourier spectrum of upward wave at the ground surface, $A_D(f)$ and $B_D(f)$ are Fourier spectra of upward and downward waves at the bottom depth (downhole installation), respectively. The wave propagation between bottom depth and surface is assumed to be vertical. However, as the plane SH-waves are polarized perpendicularly to the direction of propagation, we can easily assume also non-vertical incidence angles at the onset at the depth. The response of damped soil layers on rock is solved numerically (e.g., Kramer, 1996) by using complex shear wave velocities

$$v_S^* = v_S(1 + i\xi) \quad (4)$$

The random velocity models are then used for the computation of an ensemble of the depth-to-surface SH-wave transfer functions. An example in Fig. 2 shows an ensemble of the depth-to-surface SH-wave transfer functions computed in perturbed velocity models at the KSRH10 site (Fig. 1). Each complex transfer functions $H(f)$ is expressed by its amplitude spectrum $|H(f)|$, energy spectral density $|H(f)|^2$, and envelope delay $d\phi/df$ (Boore, 2003).

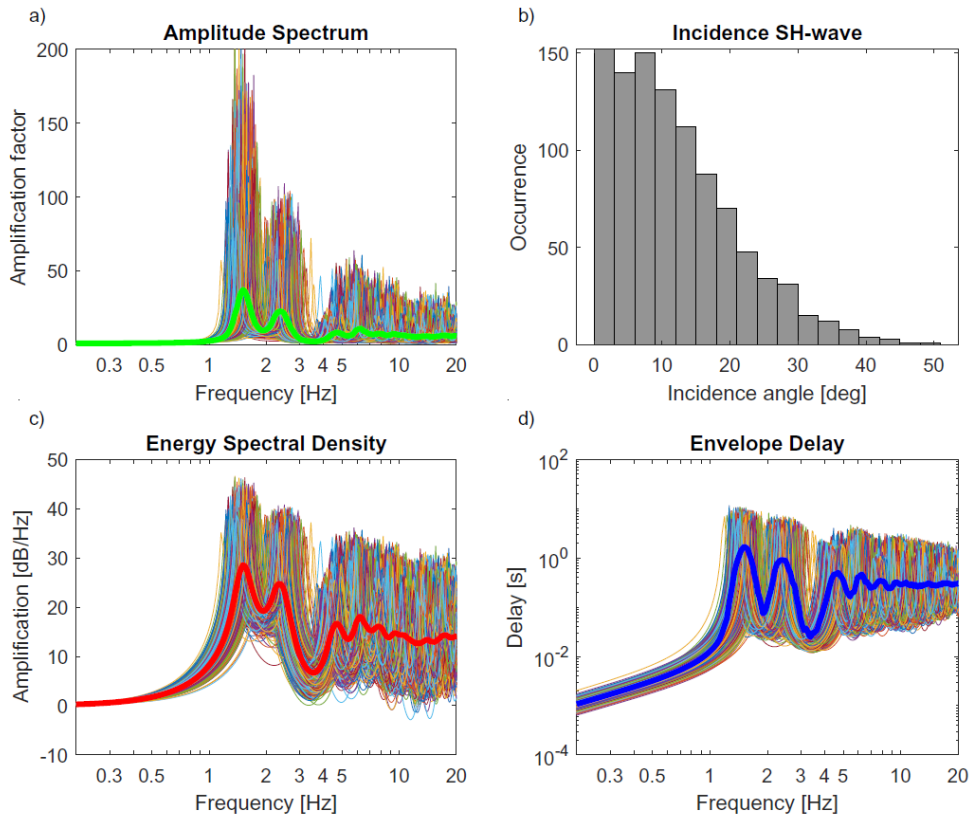


Figure 2. Ensemble of the depth-to-surface SH-wave transfer functions computed for the KSRH10 site. Panels a), c) and d) show the ensemble (thin lines) together with arithmetic mean in the respective domain (bold lines). Panel b) shows a histogram of assumed incidence angles.

Stochastic model

Then the ensemble of the depth-to-surface SH-wave transfer functions is used for the construction of the depth-to-surface stochastic model. In particular, we compute the arithmetic mean and standard deviation in the energy spectral density domain ($10 * \log_{10}(|H(f)|^2)$) and the logarithmic envelope delay domain ($\log_{10}(d\phi/df)$). The ensemble of transfer functions can be approximated by a Gaussian model in these two domains, which does not apply to the amplitude spectrum domain (see Fig. 2). An example in Fig. 3 shows the resultant depth-to-surface stochastic model at the KSRH10 site (panels b and c). The amplitude spectrum can be computed from curves in the energy spectral density as is shown in Fig. 3a. Note the difference among our stochastic model (purple), simple SH-wave amplification (light-blue), and arithmetic mean in the amplitude spectrum domain (green) in Fig 3a.

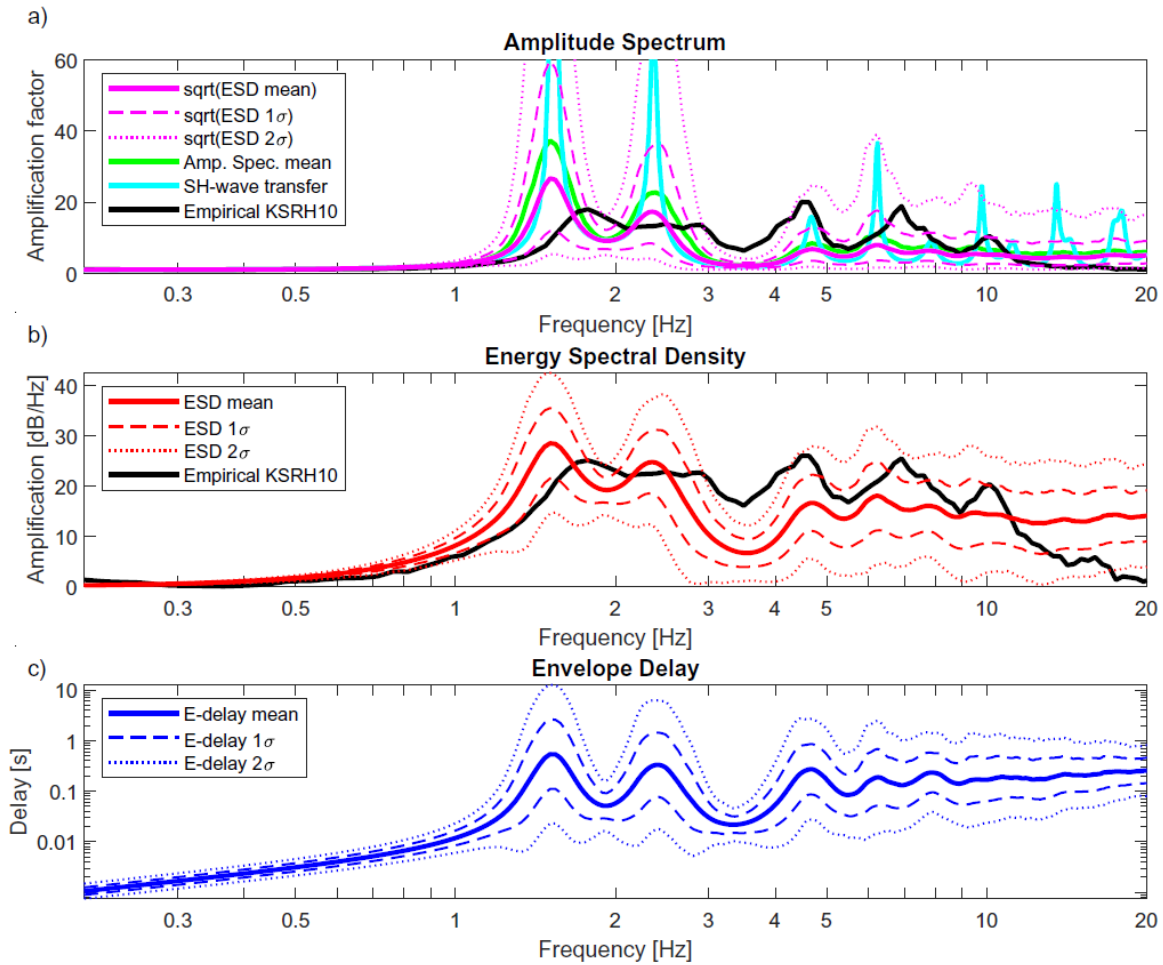


Figure 3. The resultant depth-to-surface stochastic model for the KSRH10 site. Panels b) and c) show the stochastic model by means of Gaussian statistics in the energy spectral density (amplification term) and the envelope delay (temporal term), respectively. Panel a) shows its performance in the amplitude spectrum domain.

EMPIRICAL AMPLIFICATION

Next, we exploit the peculiar configuration of KiK-net stations, computing the local amplification function as spectral ratios between horizontal-component surface and borehole recordings (surface-to-borehole spectral ratios, SBRs, see for instance Cadet et al., 2012). Specifically, we employed the triggered recordings available at the NIED strong-motion portal (NIED, 2019), and we selected events from the period 1997-2010 having hypocentral depth ≤ 25 km. Trace-windowing, computation, and

quality control of the resulting Fourier spectra are performed following Edwards et al. (2010). The considered frequency band spans theoretically the 0.1-30 Hz range; however, at every event, we retain only the spectral ratios at the frequencies for which the signal-to-noise ratio is larger than 3. All the single-event surface-to-borehole ratios referring to the same station are eventually averaged, removing the frequency abscissae with less than three contributing events. After application of the specified filtering criteria, the median number of events contributing to the SBR of each KiK-net station is about 65 across the central frequency band 0.5 – 20 Hz.

Finally, we compare our amplification prediction with the average empirical depth-to-surface amplification as retrieved from earthquake recordings. The empirical depth-to-surface amplification at the KSRH10 site is shown by the black line in Fig. 3. The comparison exhibits high similarity in the amplification values as well as frequencies of resonance peaks. There is a noticeable frequency shift of the 1.5 and 2.4 Hz resonance peaks; however, it may be explained by an inaccuracy in the reference S-wave model as discussed for this particular site by Régnier et al. (2018).

CONCLUSIONS

In this contribution, we develop and demonstrate a physical-based approach to construct site-specific depth-to-surface amplification models. Our stochastic model is constructed from an ensemble of SH-wave transfer functions by means of Gaussian statistics in the energy spectral density and the envelope delay. Unlike a simple SH-wave transfer function, our model does not possess unrealistic artificial 1D resonance peaks. We demonstrate that such a stochastic model can be used for the prediction of the depth-to-surface amplification, and we compare the prediction with an empirical depth-to-surface amplification as retrieved from the borehole installations at the KSRH10 site (KiK-net network). As we use both the amplification and time domain, the model may be used for a site-specific prediction of one-component waveforms at the surface from generic predictions at depth. Our approach has many applications, such as: the inversion on high-frequency ground motion at depth from surface recordings when knowing the velocity profile; the site-specific stochastic adjustments on classical ground-motion prediction equations; discrimination of sites with 1D resonance effects from sites with 2D or 3D wave propagation effects; adjustments of velocity profiles based on downhole array measurements; and estimation of the local effective Q when knowing the velocity profile.

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