Empirical Relationships between Shift of Horizontal-to-Vertical Spectral Ratio and Peak Ground Acceleration

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Site effects, which mainly depend on the soil's mechanical characteristics close to the earth's surface, are essential for predictions of ground motions due to earthquakes. The significant reduction of the density and stiffness compared with that at deep layers leads wave-energy to being trapped inside the shallow soil layers. It thus causes some constructive interferences amplifying the amplitude in frequency-domains, reflecting on the waveform in the time-domain. Moreover, the site effects, which are expressed by site amplification factors, will change significantly when a large shaking occurs and will reflect on Horizontal-to-Vertical spectral Ratio (HVR) by a shift from the HVR in the linear to the nonlinear case. This change in site effects is often considered as nonlinear soil effect that was identified for the first time by comparing the observed response from the 1957 San Francisco Earthquake with a model. HVR, which is the ratio of horizontal Fourier spectra with respect to vertical Fourier spectra, was utilized as a direct substitute of horizontal site amplification factors for the first time by Nakamura (1986). Recently, based on the diffuse-field theory (DFT) (Sánchez-Sesma et al, 2007; Kawase et al., 2011), HVR was discovered that it can be explained as the ratio of S-wave horizontal transfer functions with respect to P-wave vertical transfer functions from an input with vertical incidents at the seismological bedrock with a coefficient of ratio of S-wave velocity and P-wave velocity at the bedrock. If nonlinearity of P-wave-amplification during a strong shaking is ignorable, the soil nonlinearity emerging on Earthquake HVRs (EHVRs) can be regarded as the nonlinearity of S-wave-amplification. Although this kind of shift has been identified and quantified in previous studies, this study quantifies the shift with a new function for further investigations. As the first step of a series of investigations, this study mainly focuses on exploring the relationships between the shift of EHVRs and the peak ground acceleration (PGA).

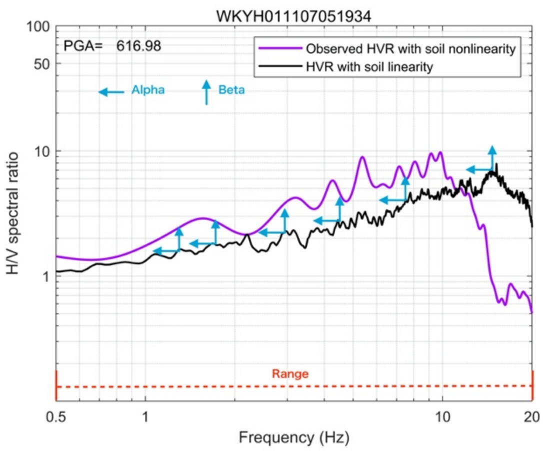

Figure 1 Example of observed EHVR with soil nonlinearity and without soil nonlinearity

$$\mathrm{DoD} = \frac{\sum_{i=1}^{n}\left(c_i \cdot \left|log_{10}\frac{\mathrm{EHVR}_{\mathrm{lin}}(f(i)\cdot 10^{\alpha})\cdot 10^{\beta}}{\mathrm{EHVR}_{\mathrm{non}}(f(i))}\right|\right)}{\sum_{i=1}^{n} c_i} \tag{1}$$

A systematic deviation can be found in Figure 1. The purple line is an EHVR in the nonlinear case from a single record observed at KiK-net (Aoi et al., 2000), named WKYH011107051934, where PGA is 616.98 cm/s^2, while the black line is an EHVR with soil linearity calculated by averaging over several weak motions with 4-15 cm/s^2 at the same site named WKYH01. Eq. (1) is proposed for quantifying this shift. Here, n is the number of frequency data of EHVR, c_i is a coefficient for balancing the weight for frequencies (the value of c_i is the reciprocal of the frequency on *the* i-th point), $f(i)$ is the frequency at *the* i-th point, $EHVR_{lin}$ is the EHVR with soil linearity, $EHVR_{non}$ is the EHVR with soil nonlinearity, and α and β are two variables that can influence the value of Degree of Difference (DoD) from the frequency and amplitude. Both $EHVR_{lin}$ and $EHVR_{non}$ are the EHVRs at the same site, although they are calculated by different methods and represent EHVRs in the linear or nonlinear cases, respectively. Based on Eq. (1), α can be seen as the shift from linearity to nonlinearity in the frequency axis, while β can represent the shift in the amplitude axis, and the DoD is considered to be an index of the goodness-of-fit of the model to observed nonlinear behavior. By changing α and β, an image can be obtained for the combination of α and β, as shown in Figure 2

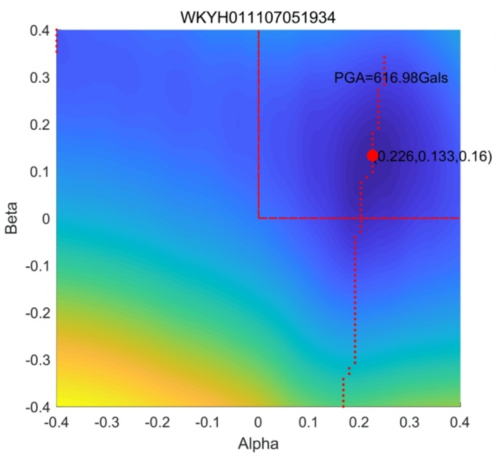

Figure 2 DoD for given combination of α and β

With the smallest DoD, α and β were selected at the red point in Figure 2, which means the best coincidence, as the real shift in both axes. Figure 3 shows the similarity between the observed EHVR in the nonlinear case and pseudo EHVR reproduced from the linear EHVR by using α and β with the best coincidence. α and β with the best matching is denoted as α_s and β_s, hereafter.

This study collected over 7000 data from 119 sites of K-NET and KiK-net (Aoi et al., 2004) in the Kinki area then calculated all the α_s and β_s from them to accomplish Figures 4 and 5. High-correlation can be distinguished after PGA is higher than 100 cm/s^2.

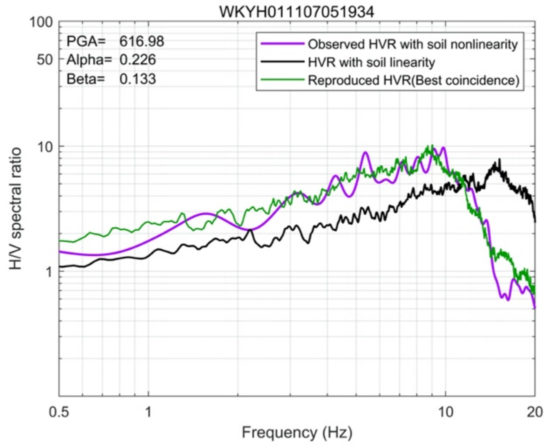

Figure 3 Similarity between the observed EHVR in the nonlinear case and pseudo EHVR

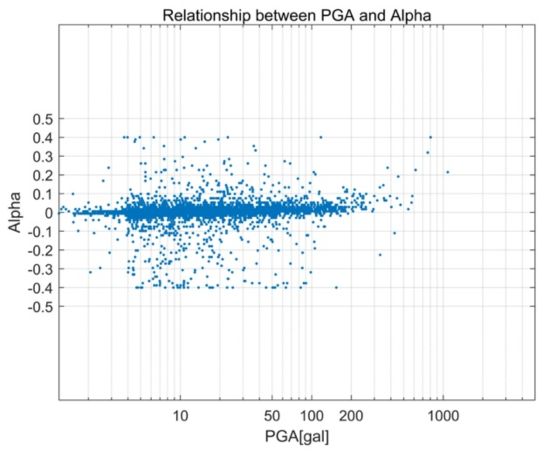

Figure 4 Distribution of α_s for all collected data

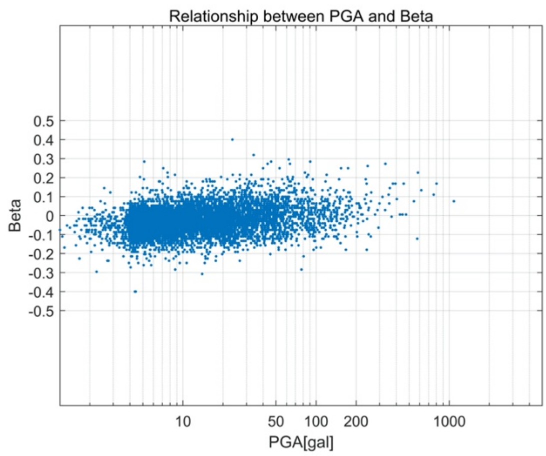

Figure 5 Distribution of β_s for all collected data