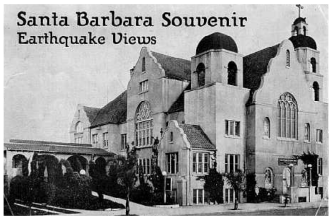

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CHARACTERIZING THE VERTICAL TO HORIZONTAL RATIO OF GROUND-MOTION IN SOFT SEDIMENT SITES

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ABSTRACT

A predictive equation to obtain the vertical to horizontal ratio of ground-motion for rock sites has been established in a first step. The method is based on the comparison between V/H of Fourier and response spectra of earthquakes with the quarter-wavelength average velocity at discrete frequencies. We extend the approach to account for resonance phenomena in soft sediment sites. In order to do so, a new parameter is defined and included in the comparison with the V/H spectra. Such a parameter is directly derived from the quarter-wavelength velocity and represents the frequency dependent seismic impedance contrast at the site. We extend the correlation in a three dimensional space which is beneficial to reconstruct the V/H of the 5% damped response spectra at soft-sediment sites for which a shear-wave velocity profile is available. We analyze 220 sites of the KiK-Net strong-motion network, selected from the entire dataset by comparison of the fundamental frequencies estimated from the recordings and by indirect modeling methods.

INTRODUCTION

In a recent study (Edwards et al., 2011) it was shown that the horizontal to vertical ratio of the ground motion for both Fourier and 5% damped response spectra (in pseudo-acceleration) can be directly linked to the local shear-wave velocity profile for sites with average velocity higher than about 800m/s (rock sites). To link the velocity estimates with given spectral ordinates, the quarter-wavelength approach (Joyner et al., 1981, Boore, 2003, Poggi et al., 2011) was used to compute average velocities. As was observed, the proposed approach was successful for those sites with rather high fundamental frequency f0>10Hz, which is generally higher than the frequency range of interest for buildings (e.g. 1-10Hz). This can be justified by the fact that below f0 the contribution of body waves in the total wave field composition is significant (Scherbaum et al., 2003). Above f0, however, and particularly for those soft sediment sites with a large contrast of velocity at depth, the influence of resonance phenomena and the generation of surface waves are important. This can therefore affect V/H ratios, which in this case does not directly depend on an average velocity estimates from the profile only.

In this paper we present a method to estimate the V/H ground motion ratio of soft sediment sites. The proposed approach extends the previous methodology from Edwards et al. (2011) to also account for the amplification effects due to resonance phenomena. To do so, a new parameter is introduced in the comparison with observed V/H ratios. The quarter-wavelength seismic impedance contrast parameter, IC^{Qwl}, is based on the estimation of the contrast of seismic velocity that a wave of given frequency can resolve at the corresponding quarter-wavelength depth. Such a parameter has been introduced in the correlation with the observed V/H and quarter-wavelength velocity representation (Vs^{Qwl}) of the measured shear-wave velocity profiles. As a result of the correlation analysis, regression coefficients are then provided for a set of discrete frequencies in the range between 0.5 and 20Hz. The presented method was tested and calibrated on a selection of sedimentary sites of the Japanese KiK-Net seismic network. We show how the results of this analysis can be used in a general way to reconstruct the V/H function between 0.5Hz and peak ground acceleration (PGA) of any sites with velocity profile of sufficient depth. We finally study the magnitude-distance dependence of the V/H relation, based on residual analysis between computed and observed H/V ratios.

THE QUARTER-WAVELENGTH SEISMIC IMPEDANCE CONTRAST

Using the quarter-wavelength average velocity (Joyner et al., 1981) alone is not sufficient to characterize the variability of the V/H ground-motion ratio in soft sediment sites. Spectral amplification induced by resonance phenomena can be described by assessing the contrast of seismic impedances at depth. This parameter, however, is not frequency dependent and therefore cannot be directly correlated with the V/H curve. For this reason, we introduce the concept of quarter-wavelength seismic impedance contrast (IC^{Qwl}). Such an approach gives the possibility of directly relating the seismic velocity contrast with specific spectral ordinates (Fig. 1).

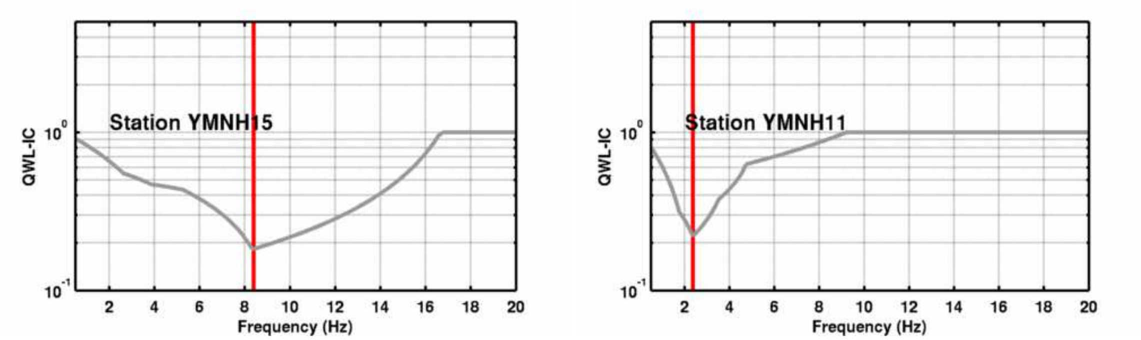

Fig. 1. Examples of the IC^{Qwl} functions for two soft sediment sites of the Japanese KiK-Net network. Is indicated in red the fundamental frequency of resonance from analytical solution.

In practice, the IC^{Qwl} can be described as the velocity contrast (eq. 1) obtained from the ratio between two quarter-wavelength average velocities (Vs^{Qwl}). The top estimate corresponds to the classic travel-time velocity averaged down to a depth (Z1) corresponding to ¼ of the wavelength of interest λ. The bottom velocity estimate is obtained as the average along the velocity profile from the depth Z1 to Z1+λ/4.

$$IC^{Qwl}(f) = \frac{Vs_1^{Qwl}(f)}{Vs_2^{Qwl}(f)} \qquad (1)$$

THE KIK-NET DATASET

In this study a Japanese dataset of earthquake recordings from the dense KiK-Net strong-motion network is analyzed (Aoi et al., 2004). The dataset includes a collection of velocity profiles (P and S) from each of the 689 sites of the network. These profiles were provided by the Japanese National Research Institute for Earth Science and Disaster Prevention (NIED) and were obtained from downhole logging in boreholes set up for the installation of buried sensors. From the 689 sites, a subset of 220 sites was analyzed in this study. The sites were selected based on the comparison of the fundamental frequencies (Fig. 2) directly estimated from the recordings and by indirect modeling methods (Fig. 3). 12963 records were used to compute the V/H ratio of the 5% damped response spectra (in pseudo-spectral acceleration) of each of the 220 selected station locations.

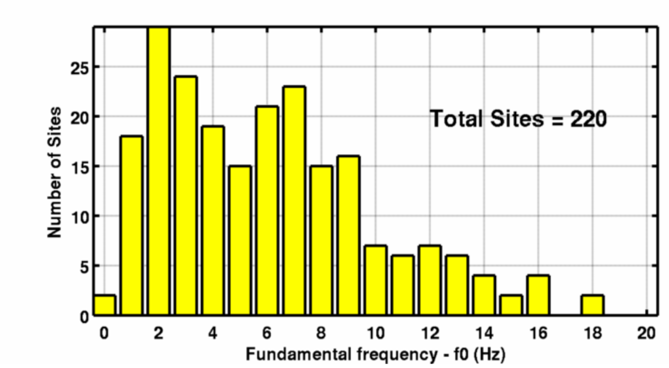

Fig. 2. Distribution of the fundamental frequency of resonance for the 220 selected sites of the Japanese KiK-Net network.

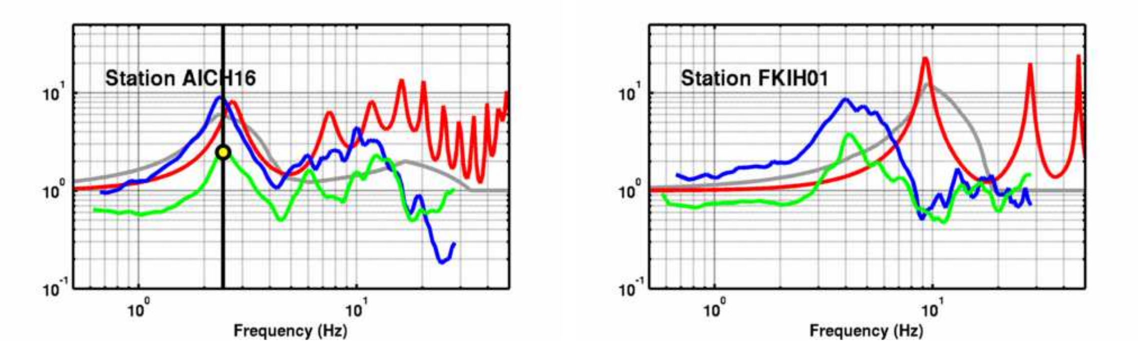

Fig. 3. Selection of the Japanese stations by comparison of the fundamental frequency of resonance estimated from H/V Fourier spectra ratio (in blue), stochastic modeling of earthquake spectra (Edwards et al., 2010, in green), SH-wave transfer function (in red) and the quarter-wavelength seismic impedance contrast (inverse, in grey). Here an example of a selected station (on the left) and a rejected one (right) is given.

V/H CORRELATIONS IN THREE-DIMENSIONAL SPACE

The V/H ratios of the 5% damped response spectra have been compared with the quarter-wavelength velocity (Vs^{Qwl}) and quarter-wavelength impedance contrast (IC^{Qwl}) in a range of discrete frequency between 0.5 and 20Hz. Different 3D regression relations to explain the data were tested using statistical significance tools. After residual analysis, the best fitting relation was found in the form:

$$\ln\left[\frac{V}{H}(f)\right] = a\cdot \ln\left(Vs^{QWL}\right) - b\cdot \exp\left(-IC^{QWL}\right) + c \qquad (2)$$

The logarithmic dependency between the V/H and Vs^{Qwl} has been kept for compatibility with a previous study (Edwards et al., 2011), while an exponential function is used to explain the data distribution along the IC^{Qwl} axis (Fig. 4). For each frequency between 0.5 and 20Hz, the coefficients a, b and c of the relation were obtained by means of a linearized optimization procedure (Tab. 1).

Table 1. Coefficients of the regression in the frequency range 0.5-20Hz. Last column shows the computed standard deviations (in log-statistic).

Freq. (Hz)	***a***	***b***	***c***	σ
0.5	0.1978	2.9084	-0.4840	1.3482
1.0	0.0547	2.0526	0.0572	1.2808
2.0	0.0590	2.2341	0.1362	1.2782
3.0	0.0964	2.0441	-0.2041	1.3170
4.0	0.1056	1.9266	-0.3186	1.3465
5.0	0.1115	1.8064	-0.4436	1.4040
6.0	0.0663	1.9083	-0.1238	1.4252
7.0	0.0556	1.8875	-0.0780	1.4240
8.0	0.0462	1.8156	-0.0651	1.4316
9.0	0.0020	1.7706	0.1818	1.4608
10.0	-0.0574	1.5746	0.4256	1.4774
15.0	-0.2851	1.3405	1.7393	1.4485
20.0	-0.1145	0.8356	0.7287	1.4099

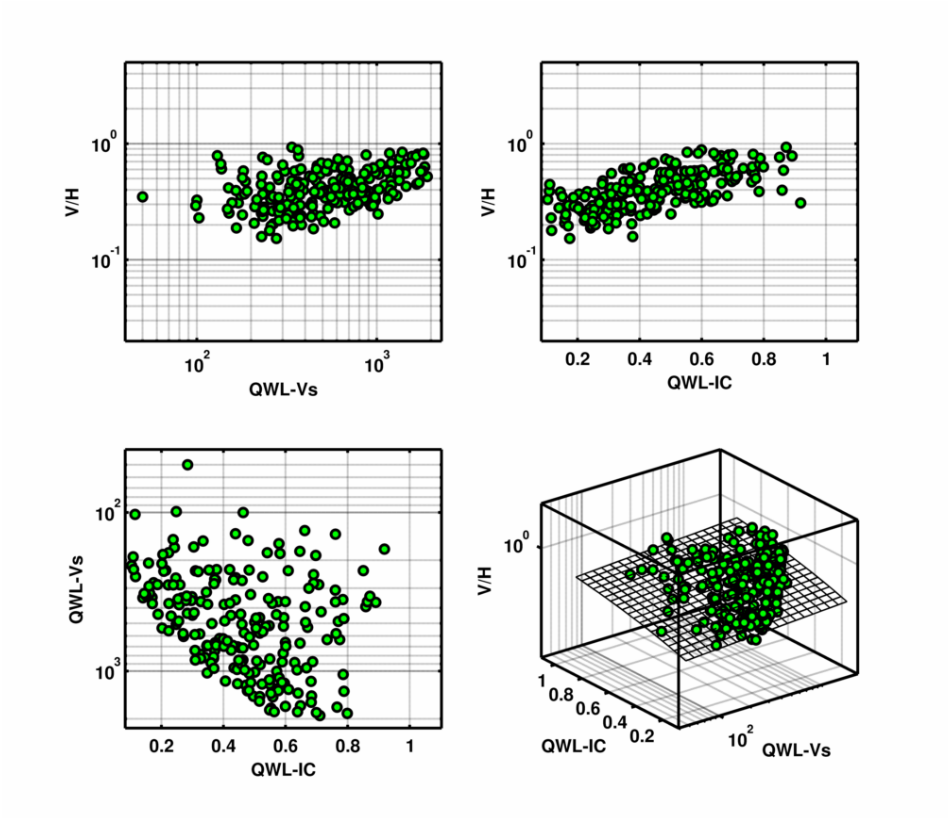

Fig. 4. Correlation between the V/H ratio of the average response spectra, the Qwl-Vs and the IC^{Qwl} parameter. For the regression, the 220 selected sites of the Japanese network were used. The plots are for a frequency of 2.5Hz.

Comparing the planar regressions over the whole analyzed frequency range show a clear trend (Fig. 5), particularly evident for the Qwl-IC. However, due to the limited resolution of the profiles at shallow depth, correlations at frequencies higher than about 10Hz were considered unreliable and not used for further studies.

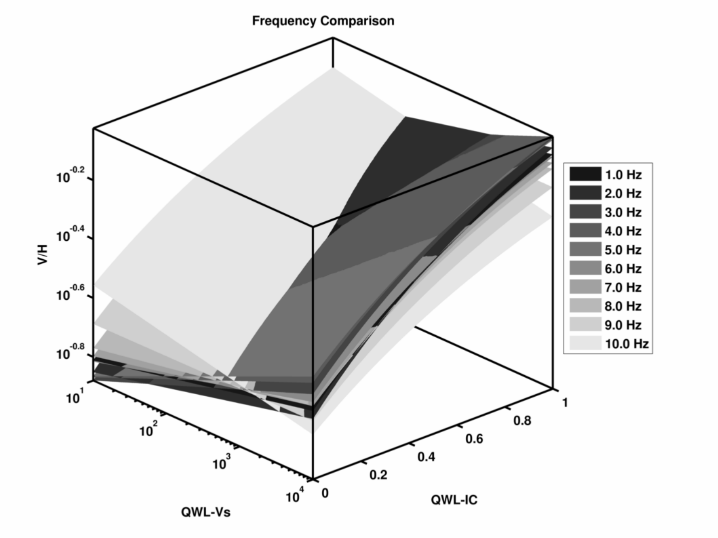

Fig. 5. Comparison of the regression results between V/H ratio of response spectra, Vs^{Qwl} (in m/s) and IC^{Qwl} of the Japanese dataset in the frequency range between 1 and 10Hz. Those planes are directly constrained by data in the range of about 100-1500m/s for the Vs^{Qwl} parameter and 0.2-1 for the IC^{Qwl}.

FREQUENCY-INDEPENDENT CORRELATIONS

Comparison of the regression results in the range between 1 and 10Hz suggest that a unique frequency independent model can be assumed to simplify the relation between V/H, Vs^{Qwl} and IC^{Qwl} in the Japanese dataset. Even if the frequency dependent models better explain the data, the uncertainty range of each distribution make the definition of a unique average model possible (Tab. 2). As a matter of fact, this simplified model fits the data equally well in the studied frequency range (Fig. 6). Moreover, such a model has the advantage that it is also easy to implement.

Table 2. Coefficients of the frequency independent correlation.

a	*b*	*c*	σ
0.0646	1.9099	-0.0902	1.3932

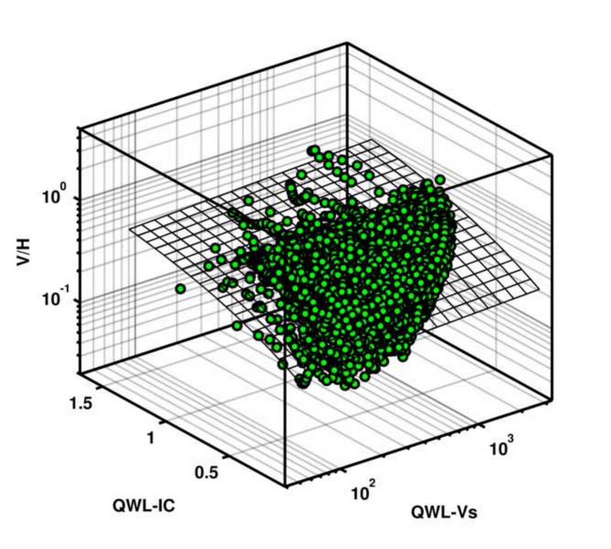

Fig. 6. Frequency independent regression obtained from fitting at the same time all frequencies in the range 1-10Hz.

BACK-COMPUTATION OF THE V/H SPECTRAL RATIO AT TEST SITES

Coefficients from the previously defined frequency dependent and the frequency independent correlations were used to back-reconstruct the V/H ratio at specific test sites of the Japanese network (Fig. 7 and 8). For each specific station location, the V/H functions were computed down to a frequency corresponding to the resolved part of the velocity profile. The curves were then compared with observed V/H to assess the robustness of the performed regression. For most of the tested sites, a good match was found, as the method also provides the possibility of reconstructing complex features of the curve, like strong V/H minima induced by resonance effects. In some cases, small discrepancies were present, probably related to some oversimplification of the Vs profile at the corresponding station location. In comparison, the use of frequency dependent or frequency independent correlations produces similar results in the whole frequency range between 1 and 10Hz (Fig. 9). As expected, however, at very high frequencies (>10Hz) large deviations are observable. In this band, the frequency independent result progressively deviates from the observation (see for example station KSRH06 in Fig. 8), as the coefficients no longer represent a good correlation with data. In a next step, the computed V/H response spectral-ratios are used to correct the high frequencies and statistically analyze the magnitude-distance dependency of the derived correlations.

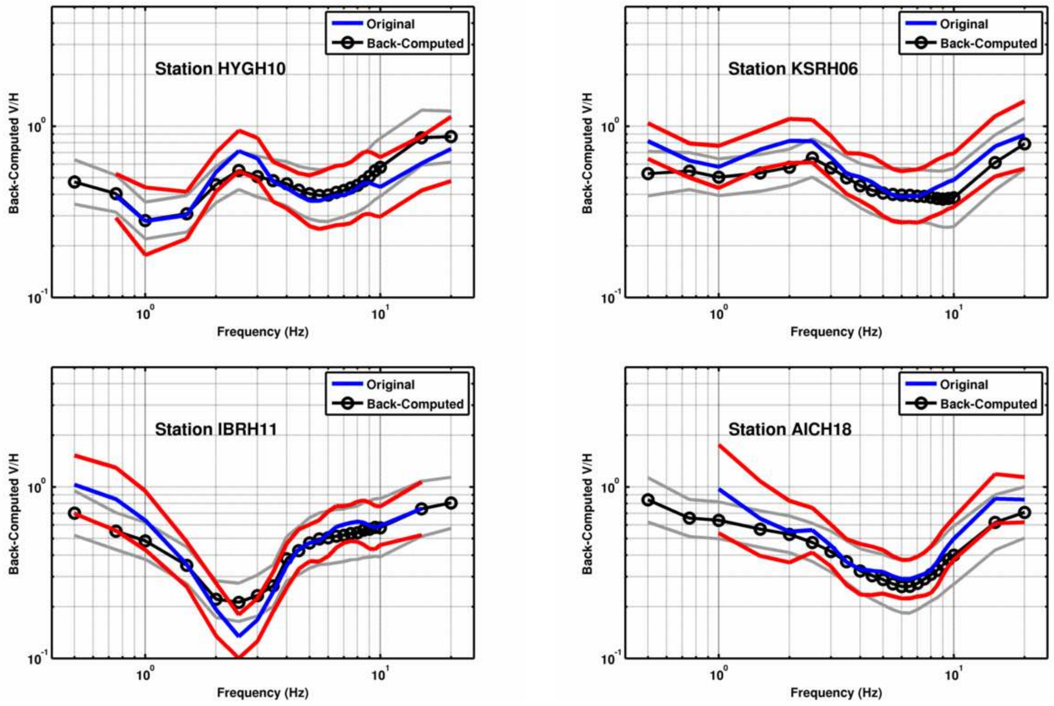

Fig. 7. Back-computation of the V/H response spectra ratio at four KiK-Net stations using the coefficients from the frequency dependent correlations. Mean and mean +/- standard deviation are given.

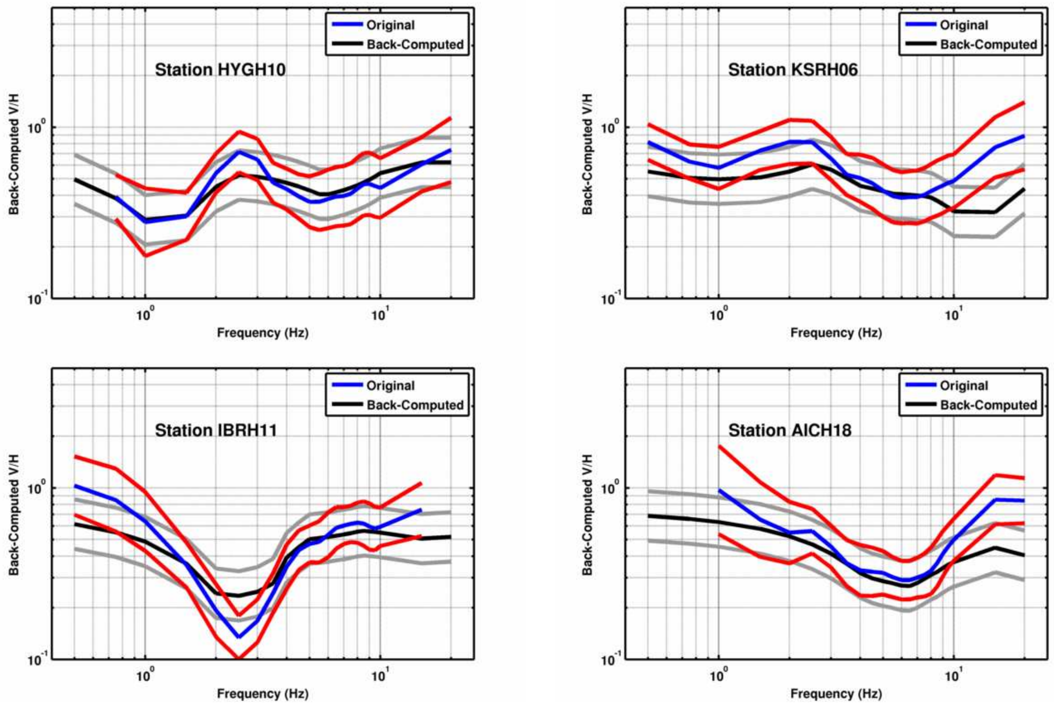

Fig. 8. Back-computation of the V/H response spectra ratio at four KiK-Net stations using the coefficients from the frequency independent correlation.

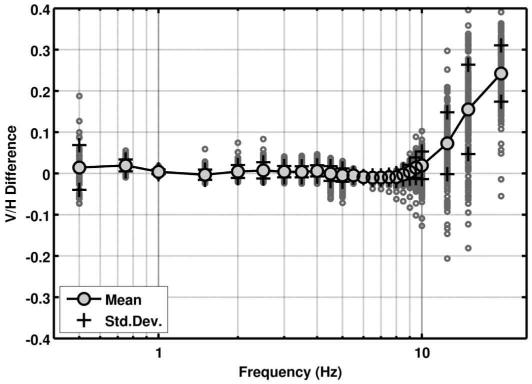

Fig. 9. Average residual distribution from the comparison of V/H response spectra ratio from the frequency dependent and the frequency independent relations. No significant deviations are observable below 10Hz.

TESTING MAGNITUDE-DISTANCE DEPENDENCE

The regressions of ¼ wavelength velocity and IC versus V/H of response spectra were used to reconstruct the expected V/H ratio at each of our selected Japanese sites. Using these predicted V/H ratios, we compared a range of recorded V/H ratios from different earthquake magnitudes and recording distances, to that expected. Any dependence on magnitude or distance should then be evident in residual plots. Plots of residual versus magnitude, distance and frequency are shown in Fig. 10, for the frequency dependent relation at the Japanese sites. There is no general trend in either magnitude or distance, although we again observe evidence for the near-field effect (R<30km) seen by Edwards et al. (2011). Fig. 11 shows the same as Fig. 10, but using the frequency independent ¼ wavelength velocity - IC - V/H regression model. No discernable difference is present to the residuals of the frequency dependent model. Fig. 12 shows the average residual as a function of frequency for the frequency independent regression model, up to 20Hz. It can be seen that the high-frequency correction proposed in Edwards et al. (2011) is also required in this case.

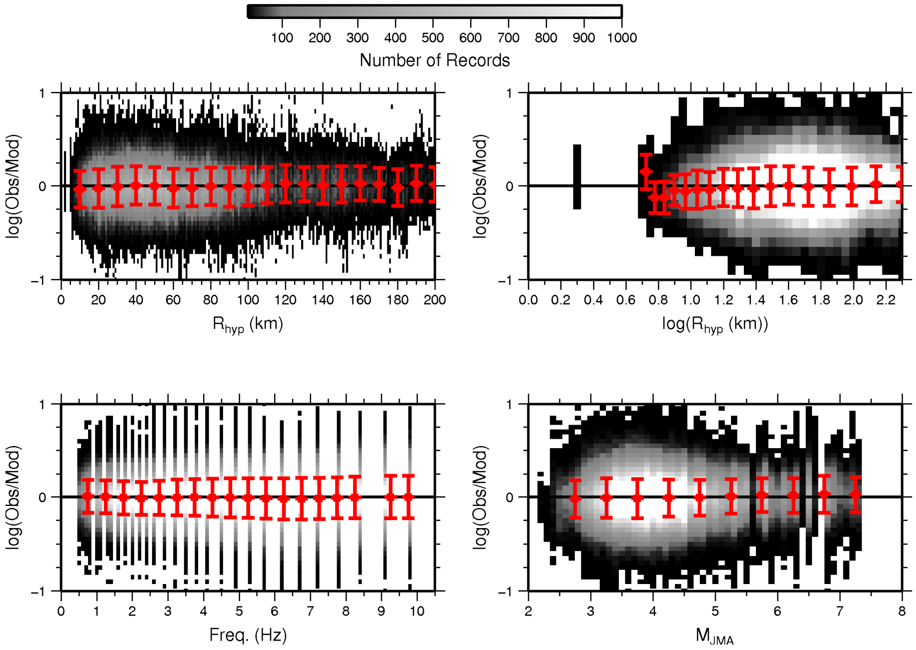

Fig. 10. Residual analysis of recorded Japanese V/H (Obs) versus V/H reconstructed using the frequency dependent V/H - ¼ wavelength velocity - IC relation (Mod) for the V/H data. Plots of residual misfit (log(Obs/Mod)) are shown for Rhyp (hypocentral distance), log(Rhyp), frequency and M (MJMA). Frequencies from 0.5-10Hz are included in all plots. The error bars indicate the mean and standard deviation of the residuals at various intervals of each parameter.

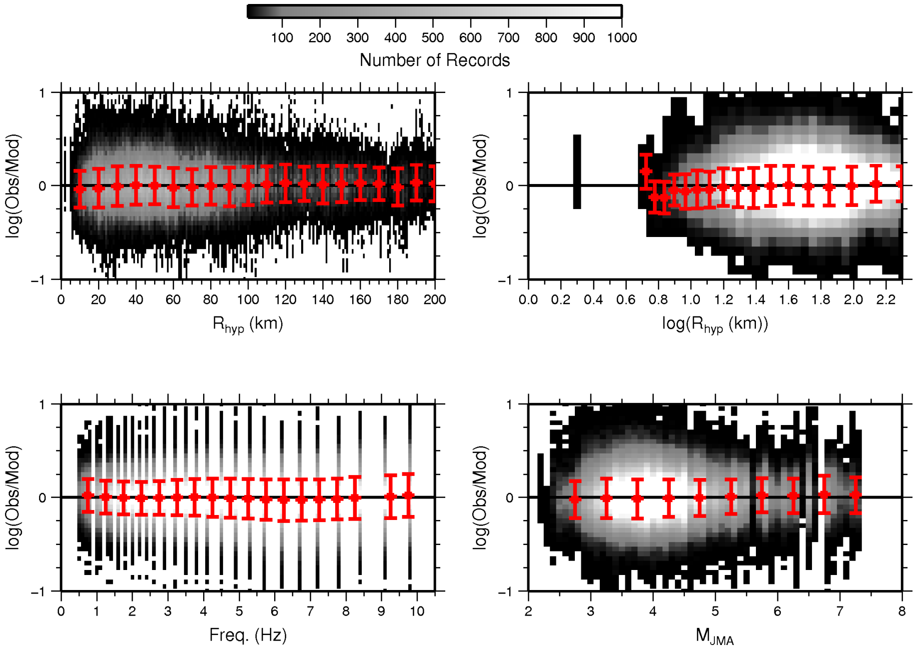

Fig. 11. As Figure 10 but comparing the frequency independent V/H - ¼ wavelength velocity - IC relation with the V/H recorded at Japanese stations.

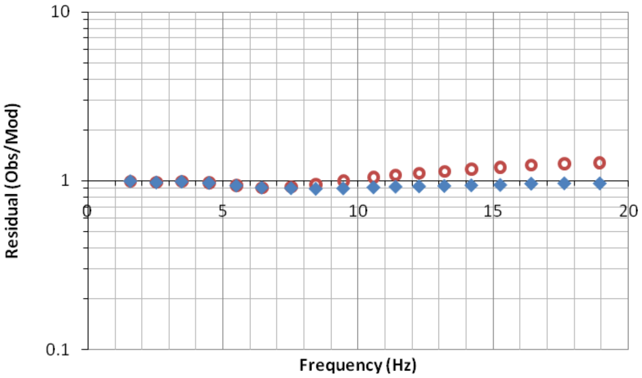

Fig. 12. Average residuals over the frequency range to 20Hz. Circles: without correction, diamonds: with correction of Edwards et al. (2011).

CONCLUSIONS

A new method to compute the V/H ratio of 5% damped response spectra for soft sediment sites has been proposed. The method makes use of the quarter-wavelength parameters (IC^{Qwl} abd Vs^{Qwl}) to link the local velocity structure at the site with the ground motion estimates at the surface. Computation of the IC^{Qwl} parameter, in particular, has been demonstrated to be a powerful tool to assess the influence of resonance phenomena on the V/H ratios. As an important outcome, it is here confirmed that the shape of the V/H functions is mainly controlled by local site characteristics, other than by the source related parameters. In practice, from the analysis, it was observed that only a negligible dependence on distance was present, while the magnitude showed nearly no effect on the average V/H ratio estimates.

The main limitation of such a procedure, however, is that a reliable and accurate assessment of the S-wave velocity structure down to a sufficient depth is required. This is directly related to the lowest investigated frequency. This information is in practice not always available, due to the high costs of most common investigation approaches. In this context, the combine use of ambient vibration techniques (such as passive array processing) can be advantageous, since it gives the possibility to obtain sufficiently accurate estimates of the velocity profiles at rather great depths with a relatively limited investment. In this study, using the Japanese KiK-Net database, we calibrated the regression coefficients in the range between 0.5 and 20Hz. Due to practical limitations of the profile resolution and the recording's SNR, however, the range 1-10Hz was considered as the most reliable. Higher and lower frequencies can be nevertheless extrapolated from the available range without any loss of generality.

As a next step, we plan to analyze the influence of the proposed quarter-wavelength parameters on the site term of ground motion prediction equations. Our goal is to reduce the total and site-specific sigma, by progressively incorporating new information from these proxies, and to obtain a more realistic assessment of the empirical amplification functions at soft sediment sites.

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