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Inversion of local S-wave velocity structures from average H/V ratios, and their use for the estimation of site-effects

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Abstract

H/V spectral ratios from microtremors are used to retrieve the S-velocity structure from a single ambient vibration record, by using its relation to the ellipticity of the fundamental mode Rayleigh wave and the amplitude of observed H/V ratio. Constraints are needed in order to restrict the possible range of solutions, and the inversion is applied to sites where the thickness of the unconsolidated sediments is approximately known from borehole information. Within the uncertainty, the inverted structures agree well with the results from other S-wave measuring techniques such as downhole and cross-hole measurements, and the analysis of ambient vibrations measured on an array. The influence of the inversion uncertainty on site-amplification estimates for earthquakes is then investigated. For all inverted models, site response is computed for a large number of events, which allows to define the uncertainty by the apriori unknown source position and mechanism of a future earthquake. In most cases the variability between the results obtained for the different models is much smaller than the variability introduced by the unknown source position. The accuracy with which S-wave velocity structures can be retrieved from observed H/V ratios is therefore sufficient for an application of the method in seismic hazard analysis for a specific site.

Introduction

The investigation of the local ground condition is an important part of any site-specific hazard assessment. One of the key parameters is the S-wave velocity structure of the unconsolidated sediments and the S-wave contrast between bedrock and sediments. These parameters together with the geometry of the bedrock-sediment interface mainly control the amplification of seismic waves during earthquakes. A prediction of amplification effects can then be performed with numerical simulation techniques.

The S-wave velocity structure can be obtained through active in-situ measurements such as S-wave seismics, surface-wave measurements with single stations or arrays, and down-hole and cross-hole techniques. Of special interest are passive methods that are based on ambient vibrations or microtremors. These methods can be applied in urban areas where in general it is not possible to carry out active measurements due to the lack of space for the experimental setup or the impossibility to use explosion sources.

All the measuring techniques have certain advantages and disadvantages. S-wave exploration seismics involves body waves in the frequency range above 30Hz, which on one hand allows to map sub-surface interface variations, but on the other hand operates in a frequency range above the frequency band of interest in engineering seismology. High-frequency waves may be strongly affected by small-scale lateral heterogeneities, and the measured velocities may not necessarily coincide with S-velocities in the frequency band below 10 Hz. One major problem of S-wave seismics is the coupling of the S-wave source to the ground, and the resulting limited penetration depth of the excited S-waves. Crosshole and downhole methods are generally time consuming and very costly.

The spectral-analysis-of-surface-waves (SASW) involves the measurement of Rayleigh-wave group- and phase-velocity to invert the S-wave velocity structure from the dispersion curves. Rayleigh waves are generated by applying vertical loading on the ground. Also with this method, penetration depth of the surface waves is limited to the upper 20 to 30 meters of soils, and in general, deeper sediments or the bedrock can not be resolved.

One method that is based on ambient vibrations is the H/V method of Nakamura (1989), which has proven to be a convenient technique to estimate the fundamental frequency of soft deposits (Lachez and Bard, 1994; Lermo and Chavez-Garcia, 1994). If borehole data can be used for calibration, the procedure has the potential to allow estimates of shear-wave velocity of the unconsolidated sediments. In one-dimensional structures, average H/V spectral ratios can be assumed to measure the ellipticity of the fundamental mode Rayleigh wave. The ellipticity at each frequency is defined as the ratio between the horizontal and vertical displacement eigenfunctions in the P-SV case, at the free surface. Hence the shape of H/V ratios can be used to estimate the shear-wave velocity profile. Yamanaka et al. (1994) and Satoh et al. (2001) applied this idea for deep sedimentary basins, Fäh et al. (2001) for shallow sites. Array methods were established by Horike (1985) after the pioneering work done by Aki (1957). These methods make use of the dispersive character of surface waves, and allow to determine shear-wave velocity profiles from the inversions of dispersion curves. The waves involved in the microtremors are surface waves as well as body waves of P and S-type, and observed wave fields are composed of several different modes which in general are not separated in time. This unknown composition of the wavefield is a major problem in microtremor methods.

Fäh et al. (2001) propose an inversion scheme to observed H/V ratios from microtremors in order to retrieve the S-velocity structure from a single ambient vibration record. For structural models with a large velocity contrast between bedrock and sediments, it has been shown that the spectral H/V ratio of ambient vibrations has stable parts which are independent of the source characteristic. These parts are dominated by the ellipticity of the fundamental mode Rayleigh wave in the frequency band between the fundamental frequency of resonance of the unconsolidated sediments and the first minimum of the average H/V ratio. The ellipticity in this frequency band is determined by the layering of the sediments. The application of a H/V-ratio method based on the frequency-time analysis allowed to locate P-SV wavelets in the time-series and to compute the H/V ratio of this wavelet. With this method the ellipticity of the fundamental mode Rayleigh wave can be retrieved for frequencies below f_0 as long as such distinct Rayleigh wavelets exist. With frequency-time analysis, the fundamental mode can be well identified also close to the minimum of the average H/V curve above f_0.

The stable parts of the H/V ratio can be related to the ellipticity of the fundamental mode and used to invert for the structure. Therefore this new method has the potential to estimate shear-wave velocities of the unconsolidated sediments from a single station at a very low cost. Here we will test the method in order to define the space of possible solutions, and to describe the limit of its applicability for different types of structures. This is the main purpose of our contribution. In particular we will compare the results from this new technique with other S-wave measuring techniques such as downhole and cross-hole measurements, and the analysis of ambient vibrations measured on an array. We will focus on the uncertainty of the inverted S-wave structures which affects the site-amplification estimates for earthquakes. We therefore compute site response for single theoretical events for the different inverted structural models. Finally a large number of events is treated, which allows to define the uncertainty by the apriori unknown source position and mechanism of a future earthquake.

Description of the method and application to a reference test site

We introduce the methodology by applying the proposed inversion scheme to a test site. We start with a description of the test site and the available data. The following theoretical and experimental sections are interspersed with results and examples from this test site.

Site description and data

Our test site is a highway underpass construction in northern Switzerland close to the city of Kreuzlingen where a variety of seismic and geotechnical experiments have been conducted (Maurer et al., 1999). The principal objective was to determine the elastic properties of a series of lacustrine clays within the 0–30 m depth range. The seismic measurements included

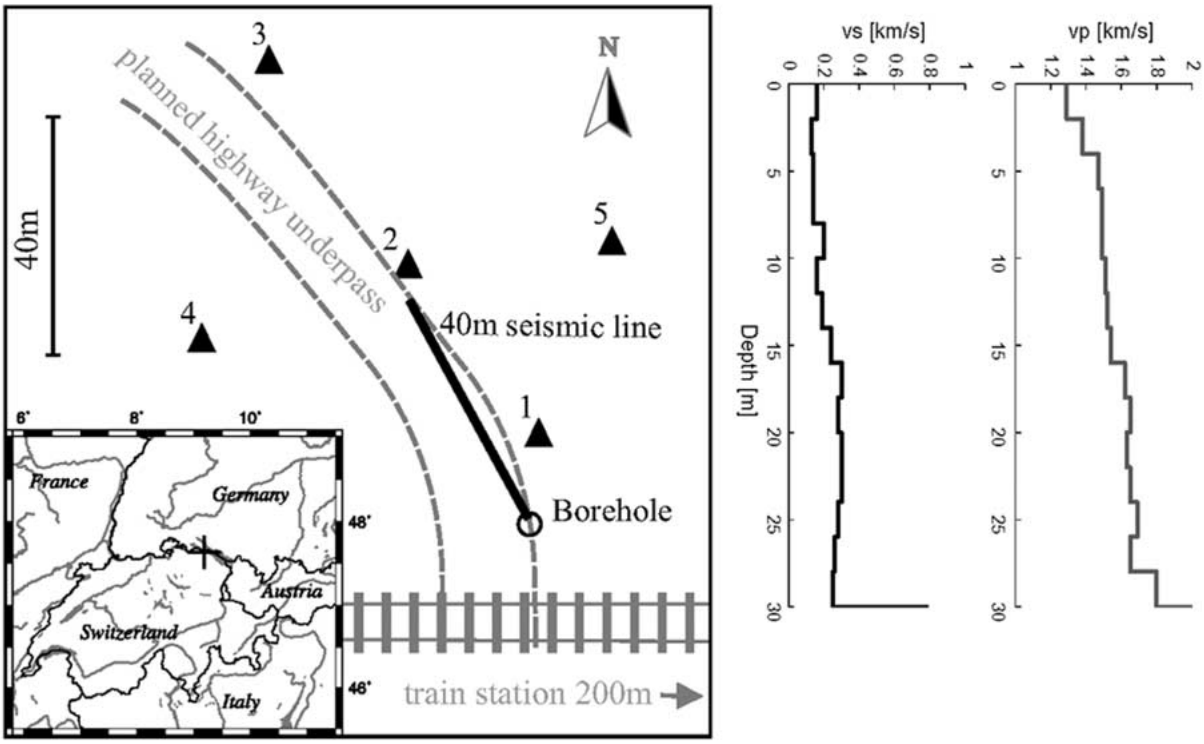

Figure 1. Overview of the reference test site. The thick black line represents the 40 m of the seismic line, the circle marks the position of the borehole and the triangles indicate the positions of the noise measurements. The velocity structure of P- and S-waves of the unconsolidated sediments from seismic measurements (Maurer et al., 1999) is given on the right. The bedrock structure was not resolved by the experiment.

surface wave measurements, reflection seismics and a seismic surface-to-borehole transmission experiment (Figure 1). For the details of the experiment, we refer to Maurer et al. (1999) and Fäh et al. (2001).

The resulting P-and S-wave velocity structure of the experiment is given in Figure 1. The uppermost 15 m consist mainly of normally consolidated lacustrine clays. Silty sands with gravel inclusions are found between 15 m and 22 m. Between 22 and 25 m the lacustrine clay units reappear. At about 25 m depth a moraine layer is found, which consists of coarse sands and gravel. The details of the moraine layer and the properties of the bedrock (Molasse) at 30 m depth cannot be resolved by the seismic survey. Due to the water saturation of the soils, the P-wave velocity is continuously increasing from 1290 to 1800 m/s.

Shortly after the other geophysical experiments a series of 5 ambient vibration measurements was recorded at the same site, the positions are indicated as triangles in Figure 1. The sensors have a period of 5s, and 15 min of signals were recorded at each sensor position. The experiment was done during the weekend, so the construction work was halted and could not influence the measurements. The signals at all five sensors were very similar, so we first focus on the results from measurement 2 in the example.

Computation of H/V ratios

Two methods are applied to compute average H/V ratios. The combination of both then allows for the inversion of the H/V ratio for the S-wave velocity structure of the site. The ambient vibration wave field is usually dominated by the fundamental-mode Rayleigh wave and the H/V curves show a very good agreement with the ellipticity of this mode.

In the classical polarization analysis in the frequency domain, the polarization is defined as the ratio between the quadratic mean of the Fourier spectra of the horizontal components and the spectrum of the vertical component. In this study the H/V polarization at a site is computed as the average from 45 windows of noise data, each of 20 s length. For each window the Fourier spectra are computed and no smoothing is applied to the spectra. The ratio is formed and the polarisations are averaged over all windows using log10

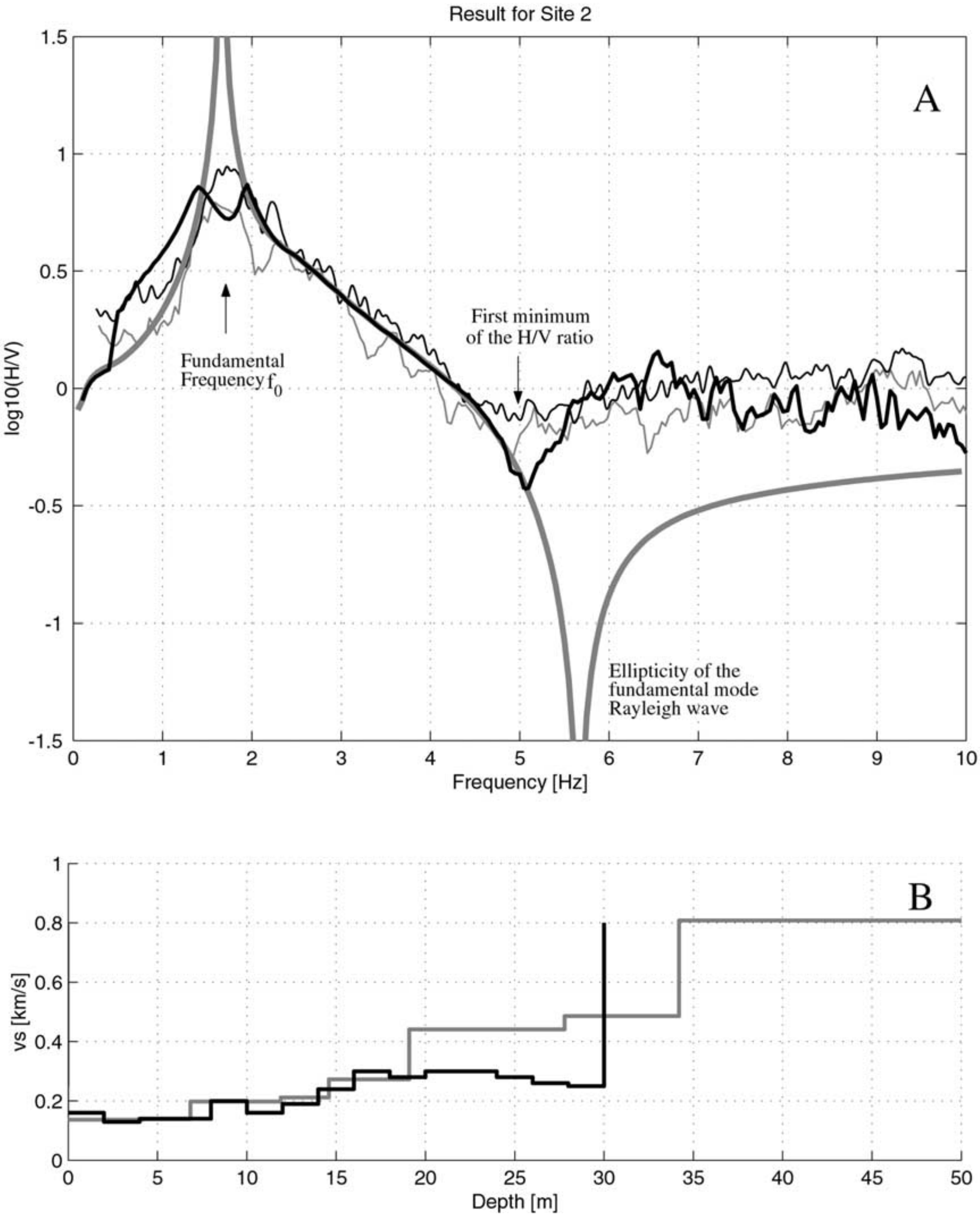

Figure 2. A) Comparison between H/V ratios of observed noise (thin lines) at observation point No.2 and synthetic noise (thick black line) for the structural model shown in Figure 2B (thick gray line). The thin black line is the result from the classical polarization analysis in the frequency domain applied to the observed signals and corrected for SH waves. The thin gray line is obtained with the method based on the frequency-time analysis. The thick gray line in the background is the ellipticity of the fundamental-mode Rayleigh wave for the inverted structure. The thick black line shows the H/V ratio of synthetic data modelled for the inverted structure. B) Structural model obtained from the inversion of the observed H/V ratios (thick gray line) compared to the model given by Maurer et al. (1999) (black line).

of the single H/V ratios. Finally the average spectral ratio is slightly smoothed. The result for the classical H/V ratio of the reference test site is shown in Figure 2A as thin black line.

The SH part of the wavefield contributes to the horizontal component of motion in the measurements. If the SH-part could be removed, the H/V ratios would better determine the ellipticity of the fundamental mode Rayleigh wave, since in the frequency band of interest the P-SV case is dominated by the Rayleigh wave. The SH-wave contribution can not be determined from a single station measurement, because source locations and mechanisms of ambient vibrations are in general unknown. This requires some assumptions concerning the spectral content of SH-waves. A reasonable assumption is that the transverse part of the wave field has a similar spectrum and energy content as the radial part. This results in a reduction factor of sqrt(2) for the H/V ratio when considering only P-SV waves. The classical H/V curves in this study are all corrected with this factor.

The second method for H/V ratios tries to reduce the SH-wave influence by identifying P-SV-wavelets from the signal and taking the spectral ratio only from these wavelets. This is done by means of a frequency-time analysis (FTAN) of each of the three components of the ambient vibrations (Fäh et al., 2001). In a frequency-time representation of the vertical signal the most energetic sections are identified in time for each frequency. We assume that this maximum is related to a single P-SV wavelet.

Because the horizontal component of the wavelet may be phase shifted with respect to the vertical component, it is selected from a time window centred at the arrival time of the maximum energy on the vertical component and with a width of one wave period. The horizontal component is selected as the maximum of the quadratic mean of the spectral values from both components and the H/V ratio is formed for the wavelet with this value. The polarization spectra with this new technique are computed for different windows of the noise data and averaged without any smoothing.

The result with this FTAN based method for the reference test site is shown in Figure 2A as thin gray line. The strong similarity in shape and amplitude supports the assumptions made for the SH-wave content for the classical method.

Inversion of the H/V ratios for the S-wave velocity structure

We now invert the H/V ratio curve under the assumption of a horizontally layered one-dimensional structure. For structural models with a large velocity contrast between bedrock and sediments, it has been shown that the H/V ratio of ambient vibrations has stable parts which are independent of the source distances (Fäh et al., 2001). These parts are dominated by the ellipticity of the fundamental mode Rayleigh wave in the frequency band between the fundamental frequency of resonance f_0 of the unconsolidated sediments and the first minimum of the average H/V ratio. The shape of H/V ratios in this frequency band depends mostly on the layering of the sediments. With the H/V ratio computation method based on frequency-time analysis, the sections of the fundamental mode can be identified close to the minimum of the average H/V curve and at frequencies below f_0, where the classical method is not conclusive. The results from both methods are combined and used for the inversion.

Due to the non-linear nature of the problem, the inversion scheme is based on a genetic algorithm. This type of inversion schemes are generally very robust and easily adapted to a specific problem. The algorithm we apply was developed by D. Carroll and does not require explicit starting models. For the inversion a number of layers is prescribed and parameter ranges fixed for the geophysical properties of the layers. The initial starting population is then generated through a uniform random distribution in the parameter space. The ellipticity of the fundamental mode Rayleigh wave is calculated for the whole population and the squared difference to the H/V ratio segments identified as ellipticity is used to define the fitness function for the evolution of the population. Throughout this study seven layers of soft sediments were used and one or two contrasting layers with higher velocities as bedrock. Below the bedrock layer a fixed standard structural model for the basement was used, as this is needed for the computation of the ellipticities.

A possible solution from the inversion is shown in Figure 2B as gray line. The maximum depth of the sediments with low S-wave velocities was limited to 35 m due to the borehole information. The ellipticity of the corresponding fundamental mode Rayleigh wave is given in Figure 2A as thick gray line and agrees very well with the H/V ratios in the frequency range between f_0 and 5Hz, and for frequencies below f_0. The inverted S-wave velocity structure is almost identical to the measured velocities (Figure 2B, black line) in the upper layers. Below 18m the structures start to differ, because the details of the moraine layer and the properties of the bedrock can not be resolved by the seismic surface-to-borehole transmission experiment.

Uncertainty of the inversion

Due to the non-uniqueness of inversion results we have to investigate the variability and uncertainty of the possible solutions by searching different models that explain the measured H/V ratios. For this purpose varying ranges for the layer parameters are prescribed and different weights are given to the segments of the H/V curve derived with the classical and the FTAN method. The variations of the parameters cover the extremes of the parameter space as well as the average ranges, so as to include the overall possible variation. The inversion procedure then provides a number of slightly differing results. The solutions have stable local maxima of the fitness function with about the same values. A solution is accepted after visual inspection of the result.

For the reference test site seven inverted structures are shown in Figure 3B, with the corresponding ellipticity of the fundamental mode Rayleigh wave overlaid to the H/V ratios of the measurements in Figure 3A. In one of the inversions the maximum interface depth constraint on the bedrock at 35 m was dropped to visualize its importance. The ellipticities are all in good agreement with the observed H/V ratios. The scatter in the velocity models is increasing with depth. The inversion is resolving with good accuracy the soft-sediment structure, but does not allow an accurate estimate of the velocity of the bedrock. The depth of the transition from sediments to bedrock is related to the average S-wave velocity of the sediment. The thinner the layer with sediments is, the lower is its average S-wave velocity. Constraints on the soft-sediment thickness are needed in order to restrict the possible range of solutions.

The peak of the H/V ratio has a certain width, so that the fundamental frequency of resonance can only be determined with a considerable error. The ellipticities found to a certain H/V ratio allow to better define the fundamental frequency of resonance f_0 by the frequency at the maximum ellipticity, as is indicated in Figure 3A.

Bedrock information

Information about the S-wave velocity of the bedrock is contained in the peak of the H/V ratio at the fundamental frequency of resonance f_0. This peak is mainly controlled by the velocity contrast between bedrock and sediment; the higher the contrast is, the larger the amplitude of the H/V ratio at the frequency f_0. Modelling of synthetic ambient vibration wave fields for each of the inverted structural models can give us indications about a possible range for the S-wave velocity of the bedrock. By comparing modelling results with the observed amplitudes of the H/V ratio, we can select those inversion results that explain the H/V amplitudes.

The modelling of synthetic H/V ratios requires some assumptions on the distribution of the source positions, and we try to keep the assumptions as general as possible by superposing a multitude of sources in a wide distance range. The numerical technique used is the mode summation method (Panza, 1985; Panza and Suhadolc, 1987) for the P-SV part of the wavefield. The method allows the investigation of signals from well-defined sources and source-receiver distances. For a given structure the P-SV modes are first calculated. From the defined source the energy content of each mode in the Fourier domain is computed, and then summed to derive the actual wavefield. In order to generate synthetic ambient vibration wave fields, multiple sources are considered. Randomly distributed sources are assumed in a certain distance range [x, x+50 m] and depth range [0 m, 50 m]. Twenty distance ranges are treated, namely [50 m, 100 m], [100 m, 150 m], . . ., [1000 m, 1050 m] with 100 different random source mechanisms for each range. For each range, the average H/V ratio is computed directly in the frequency domain from the 100 H/V ratios of the single runs with different sources. One example for such a simulation is shown in Figure 2 as thick black line for the test site. The average H/V ratios over all distance ranges fit quite nicely to the observations.

Applied to the reference test site, the input for these computations consists of the layered structures we have found in the inversion. The results for all inverted models are shown in Figure 4. We can distinguish between two groups of inverted models: those with synthetic H/V ratio peak exceeding the measured peak (thin dark-gray lines) and those corresponding to the observations (thick light gray lines). The better correspondence between observations and synthetics is obtained for the structural models with a smooth

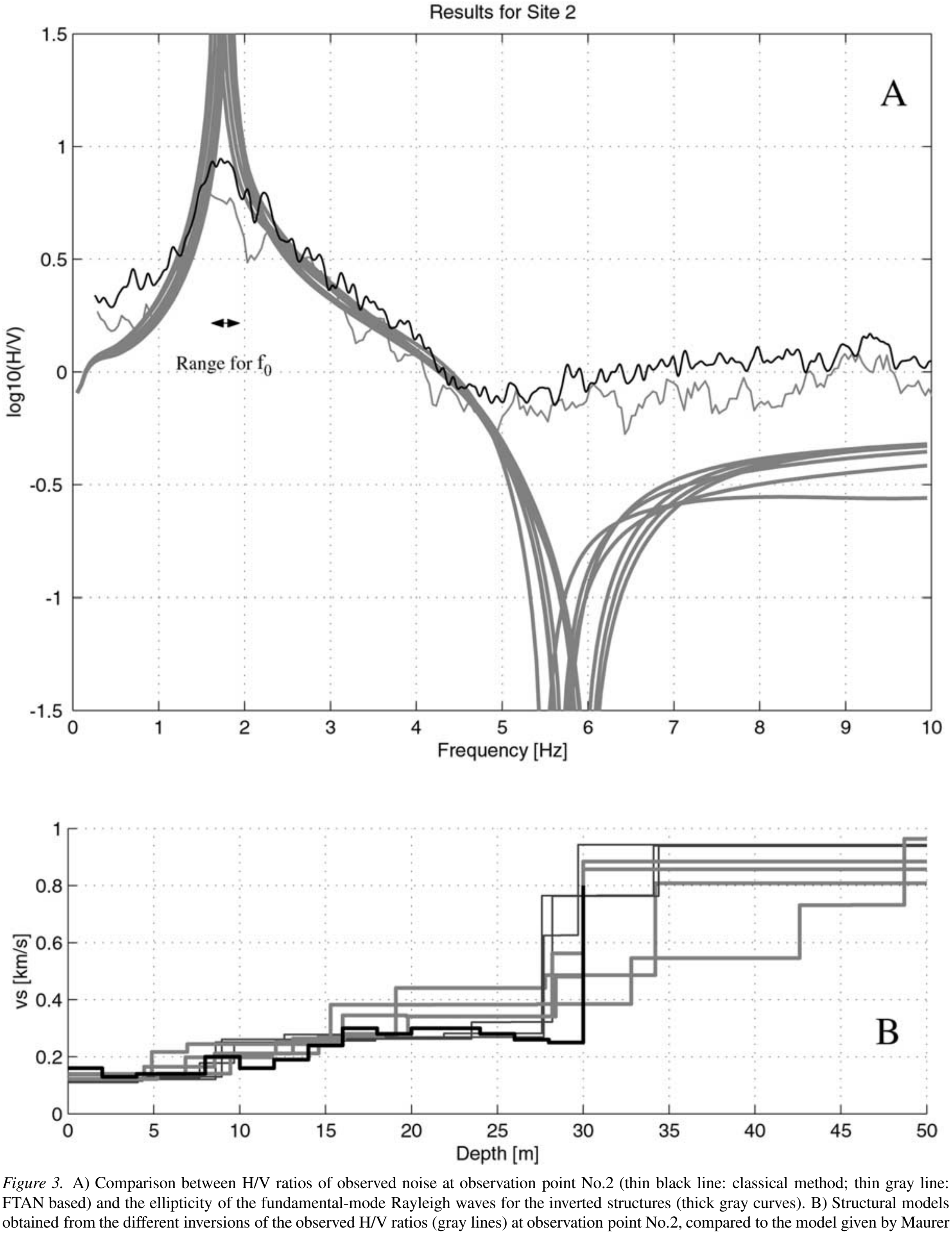

Figure 3. A) Comparison between H/V ratios of observed noise at observation point No.2 (thin black line: classical method; thin gray line: FTAN based) and the ellipticity of the fundamental-mode Rayleigh waves for the inverted structures (thick gray curves). B) Structural models obtained from the different inversions of the observed H/V ratios (gray lines) at observation point No.2, compared to the model given by Maurer et al. (1999) (black line).

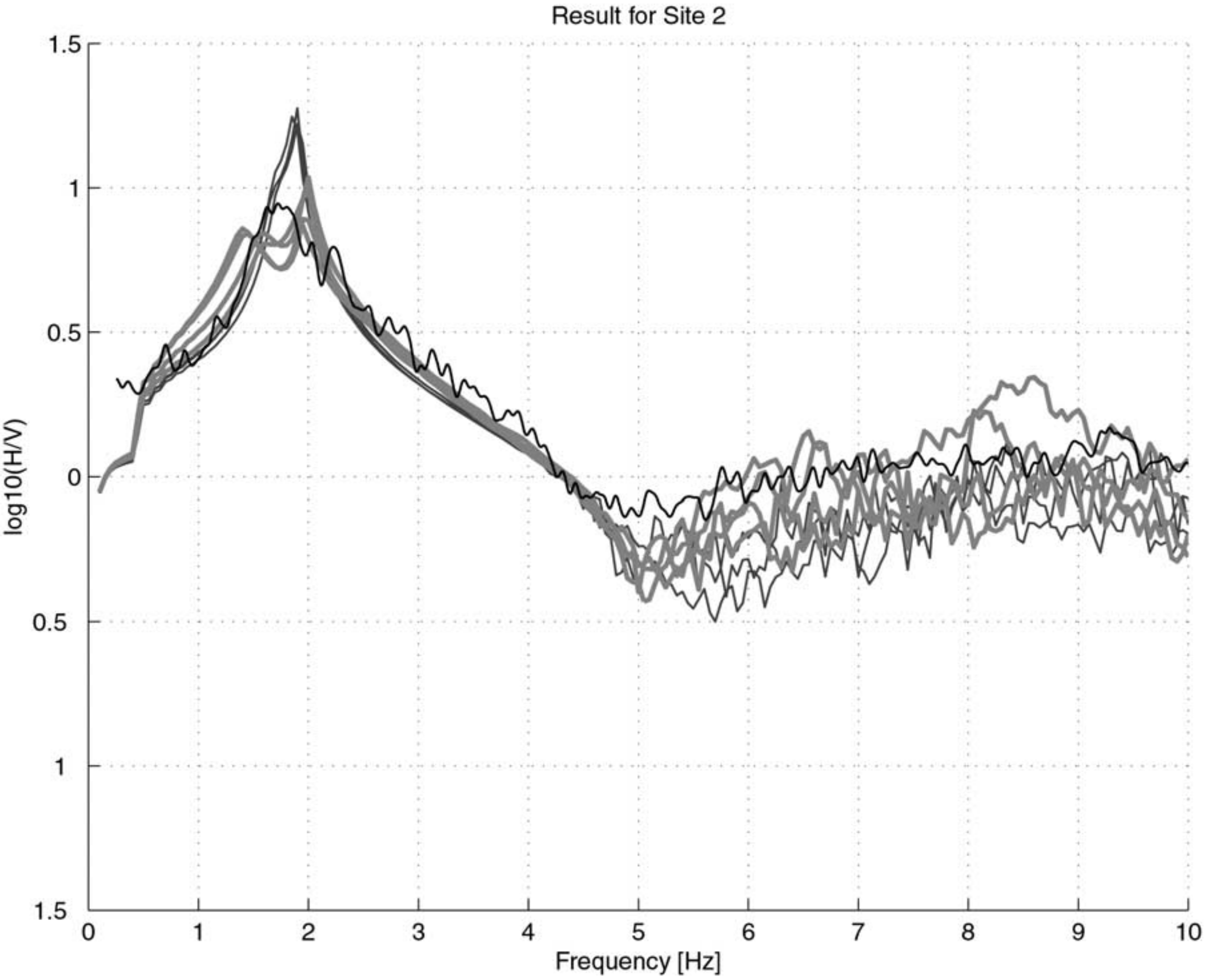

Figure 4. Synthetic H/V ratios (light and dark gray lines) obtained for the inverted structural models in Figure 3B, compared to the observed H/V ratio at observation point No.2 (thin black line).

gradient in the S-wave velocity of the bedrock (thick light gray curves in Figure 3B), which are therefore the more probable results. In this way, the modelling of synthetic H/V ratios allows to restrict the space of possible solutions, and to bound the S-wave velocity of the bedrock.

Modelling of expected amplification during earthquakes

In this section a numerical modelling technique is used to quantify the influence of the differences of the inverted structural models on seismic ground-motion amplification during earthquakes. The amplification is expressed in terms of spectral ratios and spectral amplification to a reference bedrock site. The two important factors are the reference bedrock model and the source parameters depth, distance and orientation. By numerical modelling of multiple structures and sources we try to define the variability of the ground motion and the expected amplification effects on different soils and how this variability relates to the uncertainty of the S-wave structure derived from the H/V ratios. The technique applied is the mode summation method for SH wave propagation (Florsch et al., 1989).

In a first step we consider the influence of the reference bedrock model. In Figure 5, three velocity profiles for a presumable reference bedrock are given, a low-, average- and high-velocity bedrock model. The first one defines a lower boundary for a bedrock structure, the second corresponds to a Molasse bed-

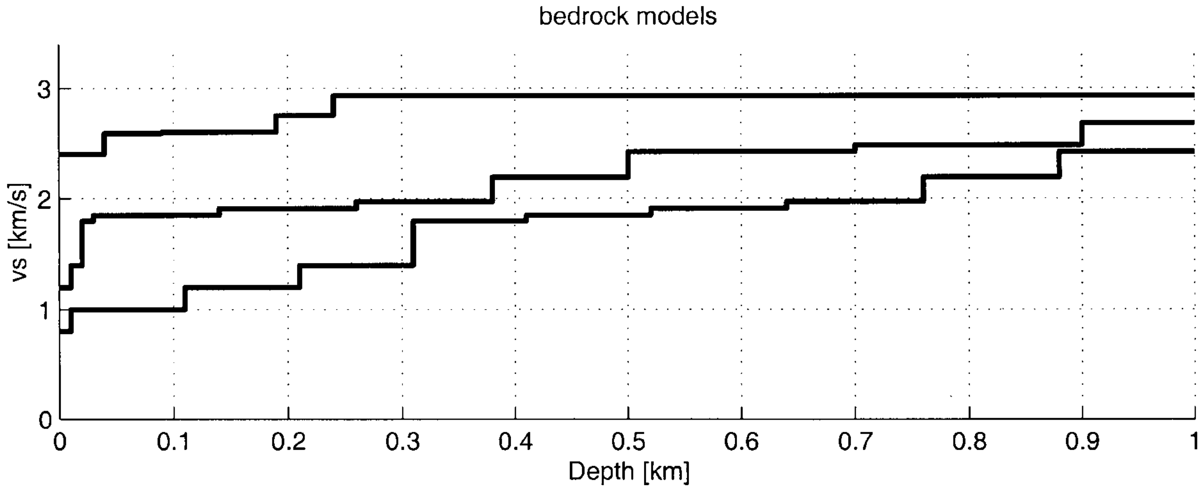

Figure 5. Three different S-wave velocity models for a bedrock reference-site: the first one defines a lower boundary for a bedrock structure, the second model corresponds to a Molasse bedrock and the third to an unweathered calcareous rock.

rock, and the third to an unweathered calcareous rock, representing the upper boundary for realistic models. The signal source is a single event located at a distance of 24 km and with a source depth of 10km. The angle between the strike of the fault and the epicentre-station line is 80°, the fault dip is 60°, the fault rake is 100°, and the source duration is 0.1 s. This is a plausible source mechanism for earthquakes in Northern Switzerland. The duration is selected arbitrarily in order to describe a non-instantaneous source. Signals are computed for the seven inversion results from the test site (Point 2) and for the three bedrock models. The reference-station method is then applied. The signals obtained for the bedrock models are the reference ground motions for the computation of spectral ratios and spectral amplifications. The spectral ratios and spectral amplifications (Sa/Sa(bedrock)) for 0% damping are given in Figure 6 for all combinations of soft sediment structures and bedrock models.

The amplification is large at the fundamental frequency of the soil column and very similar for spectral ratios and spectral amplification. For frequencies above the fundamental frequency, differences of the spectral amplification Sa/Sa(bedrock) for the different inverted models are small when compared to the spectral ratios. The computation of spectral amplification provides more stable results because it is not affected by the underflow problem in the computation of spectral ratios, and it requires no smoothing of the curves. For Sa/Sa(bedrock), the differences for the different bedrock models is considerably larger than the variation between the seven inversion result. The differences in amplification are largest at the fundamental frequency f_0 and at the higher frequencies ($3f_0$ and $4f_0$) of resonance of the soft sediments.

Secondly we study the influence of different source mechanisms and wave paths. The source parameters can be determined based on the tectonic regime or previous earthquakes in this region, or in case of only few information, they can be selected randomly. A multitude of seismic sources are defined and modelled. This step is essential in a microzonation study, since a zonation itself should not be sensitive to unknown parameters such as the source and path of future earthquakes. The double-couple sources used in the modelling are located in four distances (18, 24, 30 and 36 km), with three source depths (5, 10 and 15 km), four angles between the strike of the fault and the epicentre-station line (15°, 80°, 145° and 210°), two fault dips (60° and 85°), three fault rakes (25°, 100° and 175°) and two source durations (0.1 and 0.2 s). All combinations of the parameters amount 576 sources. The numerical simulation for one seismic source yields relative spectral amplification relative to bedrock. From the spectral amplification obtained from the 576 seismic sources, average and maximum spectral amplification are obtained for each of the inverted structural models and the three assumed bedrock models. Figure 7a shows the results obtained for 0% and Figure 7b for 5% damping.

The variation between the different inverted velocity models is very small in the entire frequency range for both the average amplification and the amplitude of the maxima. The differences in the layering

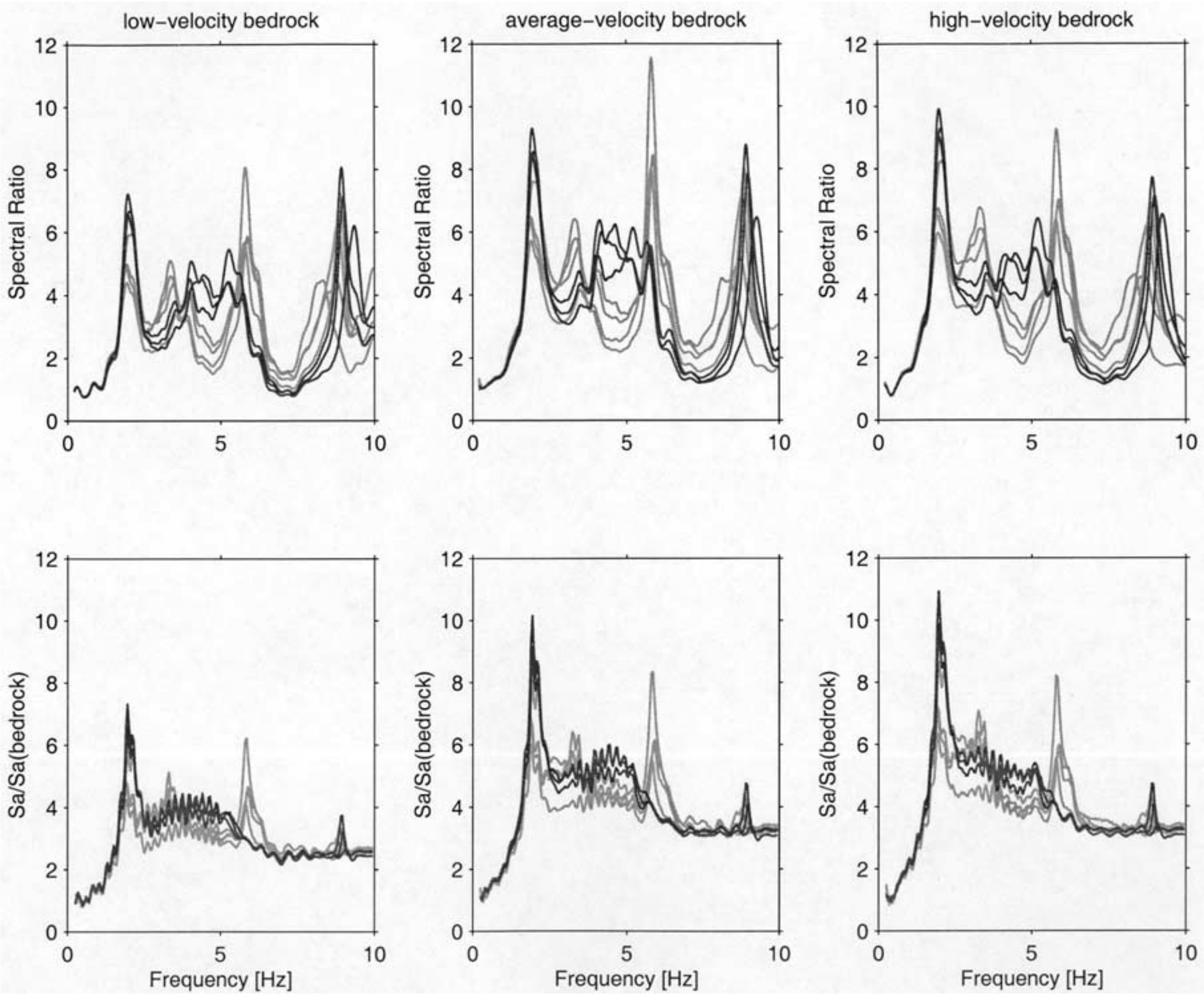

Figure 6. Smoothed spectral ratios (top) and relative spectral amplification (0% damping) obtained for the inverted structural models in Figure 3B and the three reference bedrock structures in Figure 5. Only one seismic source is assumed.

between the different structures cause the variation of the amplification. From the point of view of hazard assessment, the inverted structures are very similar for the considered frequency range. For 0% damping, the largest uncertainty in the estimate of ground motion amplification is introduced by the unknown source parameters, which can be seen by comparing the average and maximum spectral amplifications in Figure 7a. The composition of the incident wavefield therefore introduces much more variability than the uncertainty in the inverted structure. The largest peaks are obtained for the average-velocity bedrock rather than the high-velocity bedrock. This is also due to differences in the composition of the incident wavefield and different incidence angles for the different bedrock models. For the amplification at 5% damping, shown in Figure 7b, the variability introduced by the source position is strongly reduced for the low-velocity and average-velocity reference bedrock, and it is of about the same order as the variability introduced by the differences in the inverted structural models. The lowest amplification is obtained for the model without a bedrock depth limit of 35 m. For the high-velocity reference bedrock, the variability introduced by the unknown source remains higher than the variability introduced by the different inverted models. In general, amplifications are smaller for the structural models with a smooth gradient in the S-wave velocity of the bedrock (light gray curves in Figure 7a and 7b), and a smaller amplitude of the H/V ratio (see Figure 4).

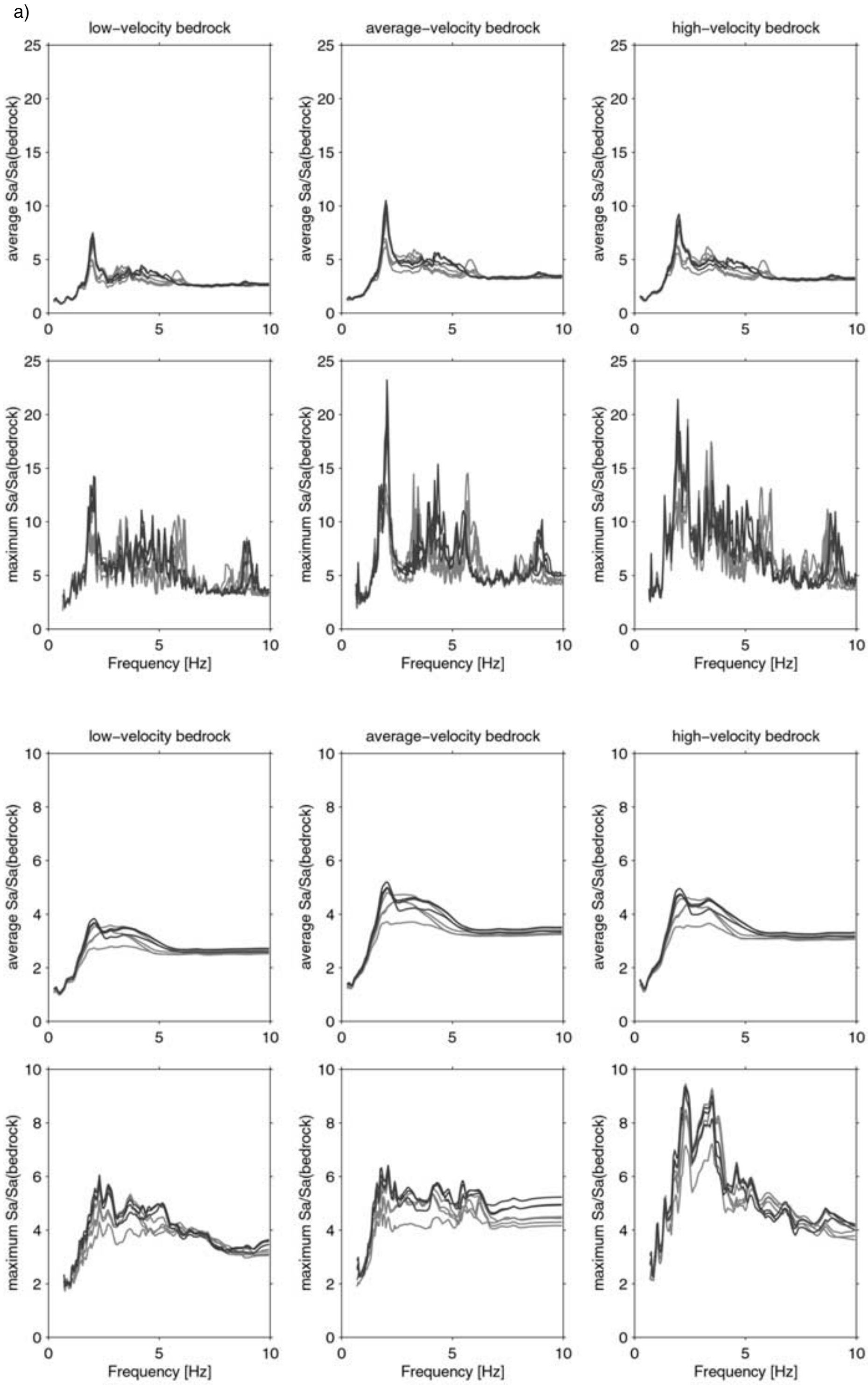

Figure 7. Average (top) and maximum spectral amplification, obtained for the inverted structural models in Figure 3B and the three reference bedrock structures in Figure 5, assuming 576 seismic sources at different distances and depths, and with different mechanisms. The spectral amplification are given for a) 0% damping and b) 5% damping. Black lines correspond to the inverted models where the modelled H/V peak exceeds the observation (strong velocity contrast), while gray lines are from the models where the synthetic H/V ratio fits the observation better.

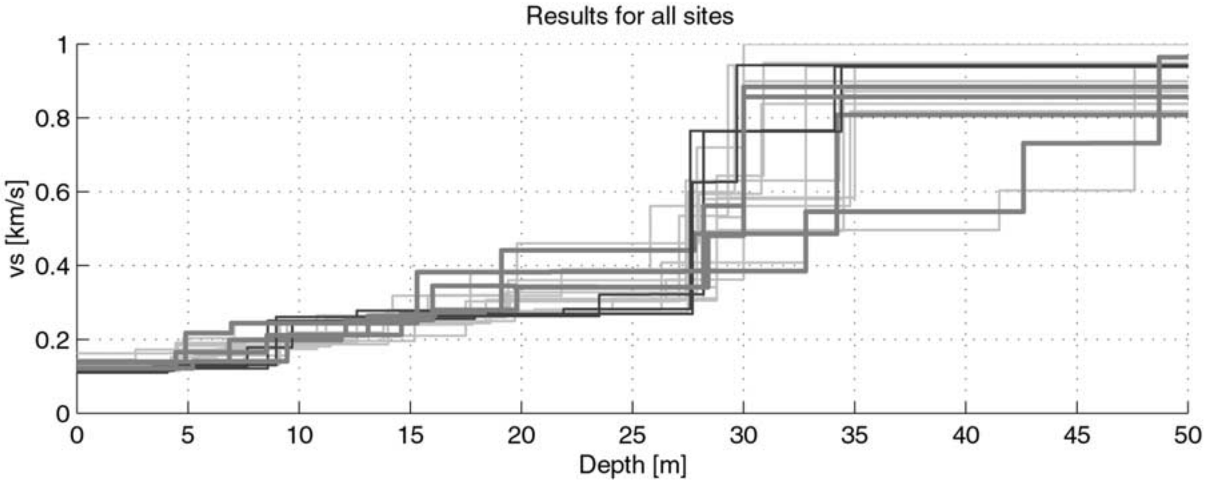

Figure 8. Structural models obtained from the different inversions of the observed H/V ratios (gray lines) at observation point No.2, compared to the inverted models for the other four observation sites shown in Figure 1.

A microzonation or an evaluation of site effects should not be performed for single points, but for an area of a certain dimension. This introduces an uncertainty due to the lateral variations of the structure. Multiple measurements over the area have to be analysed to insure the reliability of the results. Applied to the reference test site, this can be taken into account by analysing the H/V ratios obtained at all five observation points (Figure 1), and by inverting for possible S-wave structures. Figure 8 compares the inverted structural models at all observation points. The scatter introduced by the possible structural models for all sites is only slightly increased compared to the results for site 2. This confirms that the structure under consideration can be approximated by a one-dimensional layered model. Testing of the hypothesis of a 1D structure could also be performed by mapping the change of the fundamental frequency and shape of the H/V ratio in the area.

Comparison with an array method

So far we applied the H/V ratio inversion to one test site. To further validate the method, we apply it to two additional sites, where the S-wave velocity structure of the sediments had been measured with a surface wave inversion from ambient vibrations on a small scale array. We shortly explain the array technique, show the data and results from the H/V method and then discuss the findings.

Array method

Noise recordings on small aperture arrays can be used, through an analysis of spatial correlation, to measure phase velocities of surface waves and invert the surface velocity structure. A first study in Switzerland (Kind et al., 2001; Kind, 2002) with the high-resolution beamforming illustrated the practical interest of this technique, and provided S-wave velocity measurements that can be used to validate the single station H/V method. The array method allows for the extraction of the fundamental mode Rayleigh wave dispersion from the ambient vibration wave field recorded on a small scale array (aperture 50–200 m) by estimating the f-k-spectrum of the wave field. The dispersion curve can then be inverted for the S-wave velocity structure. The method can be applied to any site where the wave field can be approximated as plane waves. The scheme used for the inversion of the dispersion curve in the array method is the same genetic algorithm as for the H/V ratio inversion. As with the H/V technique the inversion is not unique and several probable models result from different velocity ranges defined for the layers. The bedrock velocities are much better constrained by the dispersion curve.

Industrial Test Site

The first site is located in a alluvial valley close to a river in northern Switzerland. It has shallow sediments mostly consisting of gravels, with a total thickness of 25 to 35 m, known from several boreholes at the site. The bedrock is composed of hard calcareous

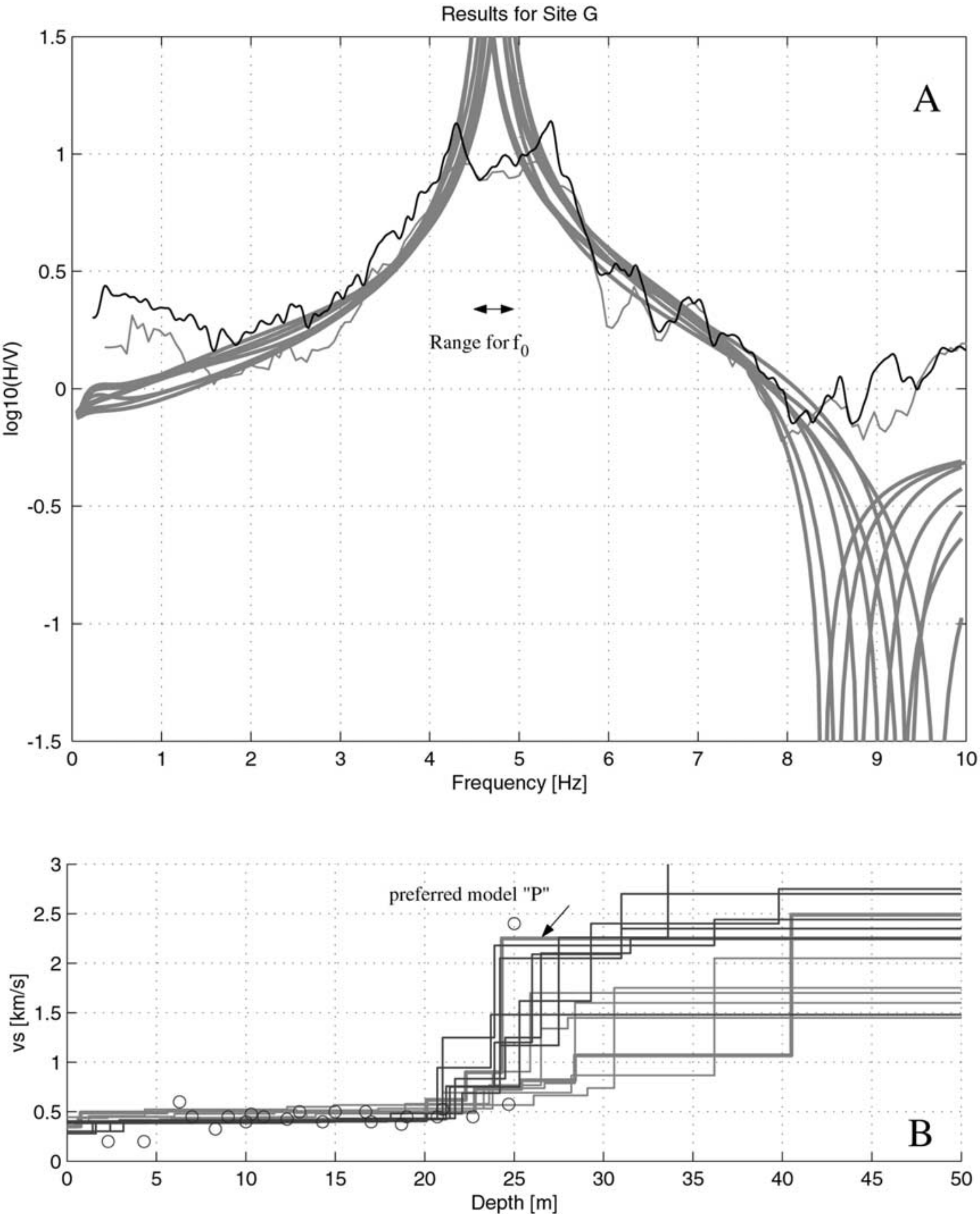

Figure 9. A) Comparison between H/V ratios of observed noise at the second test site and the ellipticities of the fundamental-mode Rayleigh wave for the inverted structures (thick gray curves). B) Structural models obtained from the different inversions of the observed H/V ratios (gray lines) at the second test site, compared to possible models obtained with the high-resolution beamforming array method (dark lines). Results from a cross-hole experiment are shown as open circles. This cross-hole site is just beside the area of the array experiment. The preferred model 'P' from the H/V inversion is indicated.

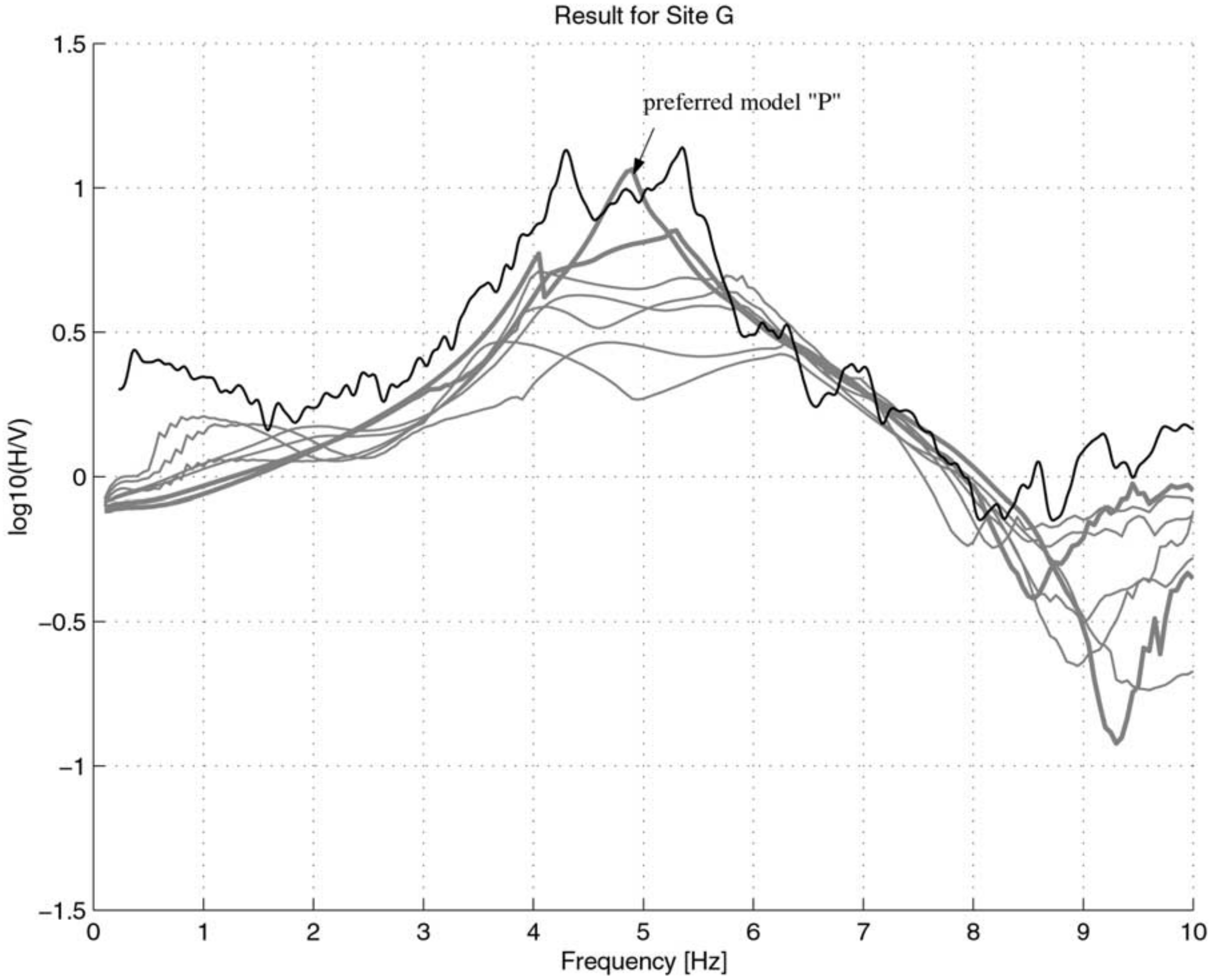

Figure 10. Synthetic H/V ratios obtained for the inverted structural models in Figure 9B, compared to the observed H/V ratio at site G. The result for the preferred model 'P' from the H/V inversion is indicated.

rocks, and we can expect S-wave velocities of the order of 1.9–2.4 km/s, giving a large contrast to the sediments. The main source for the ambient vibrations is an industrial site just beside the measuring area. A measurement with the array method has been done at the site with an array of 7 sensors with an aperture of 50 m. A sample of 15 min of ambient vibrations was recorded at the centre of the array for the H/V method.

The H/V ratios are calculated with both the classical and the FTAN method and the inversion was applied to the results. In Figure 9A the H/V ratio from the classical method is shown as thin black line, corrected with a factor of $\sqrt{2}$. The thin gray line is the result from the FTAN based H/V ratio. Thick gray lines show the ellipticity of seven probable inverted velocity structures, while the S-wave velocity structures themselves are shown in Figure 9B as gray lines and results from the array measurement as black lines. To constrain the bedrock velocity from the H/V ratio inversion, synthetic H/V ratios for the structural models were obtained (Figure 10, gray lines). The observation (thin black line) agrees best with a bedrock model with high velocities (Preferred model 'P'). The preferred model obtained with the H/V method is model P in Figure 9B with a sediment thickness of about 22–24m and an average velocity of about 400 m/s.

In general the agreement between the two methods is very good. The velocities for the sediment layers are slightly lower in the array measurements by about 10%. The difference might be caused by the deviation of the wave field from plane waves, as the distance from the industrial sources to the array is only in the order of twice the array diameter. The bending of the real wave front causes an apparent slower velocity in the array measurements. Furthermore the array results represent the average structure for the area of the array layout, while the H/V curves reflect a local area of more restricted size. The high bedrock velocities agree very well with the structural model from the array.

After the completion of this site study, we had access to unpublished results of a cross-hole experiment that was performed about 30 years ago before the construction of the industrial complex. The borehole sites are just beside the area of the array experiment. Two experiments were performed at that time, with three boreholes. The distance between two boreholes have been 6.2 m and 7.9 m. The result of this experiment is also given in Figure 9B. The estimated error of one crosshole measurement can be up to 20%. The S-wave velocities and their variability is exactly in the range of the results obtained from the ambient vibration experiments.

The results from computations of average and maximum spectral amplification for 5% damping are shown in Figure 11. As for the first test site, the large difference between average and maximum amplification indicates that the variability introduced by the assumed source positions is much larger than the differences from the inversion uncertainties.

Test Site Hardwald

The second test site is located within a forest in a recreational area outside the city of Basel. The ambient vibration sources are therefore assumed to be located distant from the observation point, and the approximation of plane waves holds. The surficial geology is well known from many boreholes drilled for ground water control. The site consists of 30–40 m of Holocene and Pleistocene gravels covering a layer of soft material with unknown thickness. Below, hard calcareous rocks are assumed to form the seismic bedrock. An array measurement was performed at the site with 13 sensors and an aperture of 200 m. For the H/V method 15 min of ambient vibrations were recorded at the centre of the array.

The applicability of the H/V method is at the limit when the contrast between bedrock and soft sediments is small or when a deep basin with a strong S-wave velocity gradient is analysed. Then we can observe small amplitudes of the H/V ratio. A dominant amount of energy from higher-modes Rayleigh waves, P- and SH waves can then contribute to the ambient noise in all frequency ranges, and the upper flank of the main peak in the H/V ratio is not only determined by the fundamental Rayleigh mode.

Another problem arises when the assumption concerning the spectral content of SH-waves is not correct, and the H/V curves calculated with the classical and the FTAN method separate. This has been observed at several sites located in deep sedimentary basins in Switzerland. The site Hardwald represents a typical case where we observe this separation. In Figure 12A the H/V ratio from the classical method is shown as thin black line, corrected with a factor of $\sqrt{2}$. The thin gray line is the result from the FTAN based H/V ratio. There are two possible explanations for this separation: the first reason could be that the contribution of SH waves exceeds the energy of the fundamental mode Rayleigh wave in the entire frequency band of interest; the second explanation could be that well-separated wavelets of Rayleigh waves do not exist in such structures.

Despite these problems we determined possible velocity structures for this site which explain the observed H/V ratios (Figure 12A). The results of the inversions are given in Figure 12B as gray lines and the corresponding ellipticities of the fundamental mode Rayleigh wave in Figure 12A as thick gray lines. No attempt was made to derive bedrock information from synthetic modelling of the ambient vibration wave field. The results from the array method are shown as thin black lines in Figure 12B. There is a good agreement of the sedimentary layers between the two methods, while in the bedrock the H/V ratio derived structures vary largely, as had to be expected. The array measurements for the sedimentary layers had been further confirmed by S-wave reflection seismics (Kind et al., 2001), so the inversion results from the H/V ratios are validated for a third site.

Again the difference in expected amplification between the results from the two methods are validated through the computation of spectral amplification for 5% damping. The results are given in Figure 13. The variability between average and maximum spectral amplification is again much higher than the variability between the results obtained for the different inverted structural models.

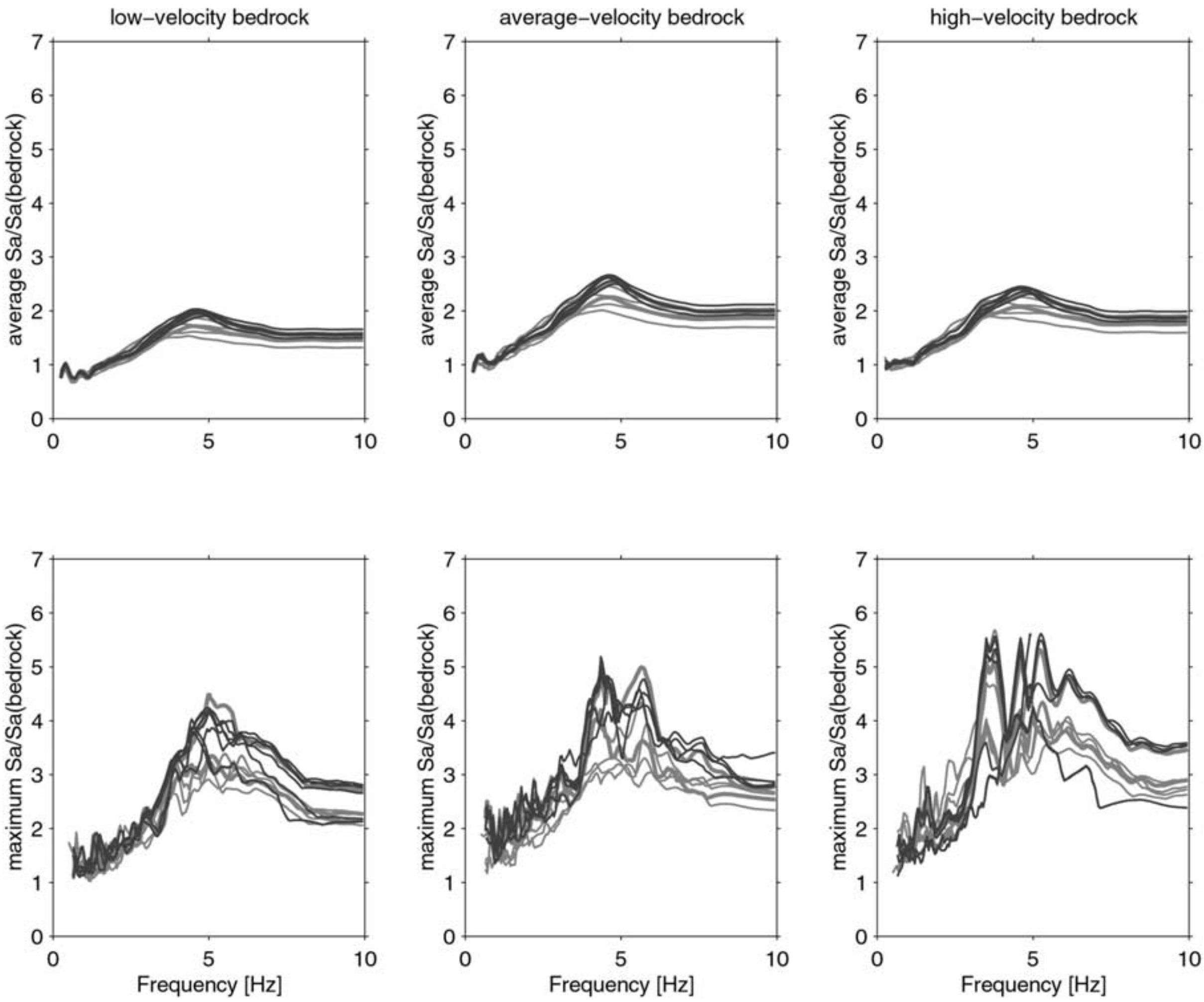

Figure 11. Average (top) and maximum spectral amplification for 5% damping, obtained for the inverted structural models in Figure 9B and the three reference bedrock structures in Figure 5, assuming 576 seismic sources at different distances and depths and with different mechanisms. Amplification for structures obtained from the H/V ratio (gray lines) and from HRBF method (dark lines) are shown.

Conclusions

We have shown that the H/V ratio can be used to determine reasonable S-wave velocity models for a site, if the structure is characterized by a large velocity contrast between bedrock and sediments, and as long as the site can be approximated by a layered structure. For such structures, the H/V ratio has stable parts that are dominated by the ellipticity of the fundamental mode Rayleigh wave in the frequency band between the fundamental frequency of resonance of the unconsolidated sediments and the first minimum of the average H/V ratio. The ellipticity in this frequency band is determined by the layering of the sediments. The comparison with other S-wave measuring techniques confirmed the results obtained from the H/V ratios.

Constraints are needed for the inversion in order to restrict the possible range of solutions. The inversion can preferably be applied to sites where the thickness of the unconsolidated sediments is known from borehole information or from a seismic survey. At sites where the thickness is unknown, the inversion can only be applied when the bedrock velocity and layer thickness can be estimated within a reasonable range. A comparison between H/V ratios obtained with numerical modelling of ambient vibration wave fields and observations allows a selection of preferred models from a set of structural models that all explain the observed H/V ratio.

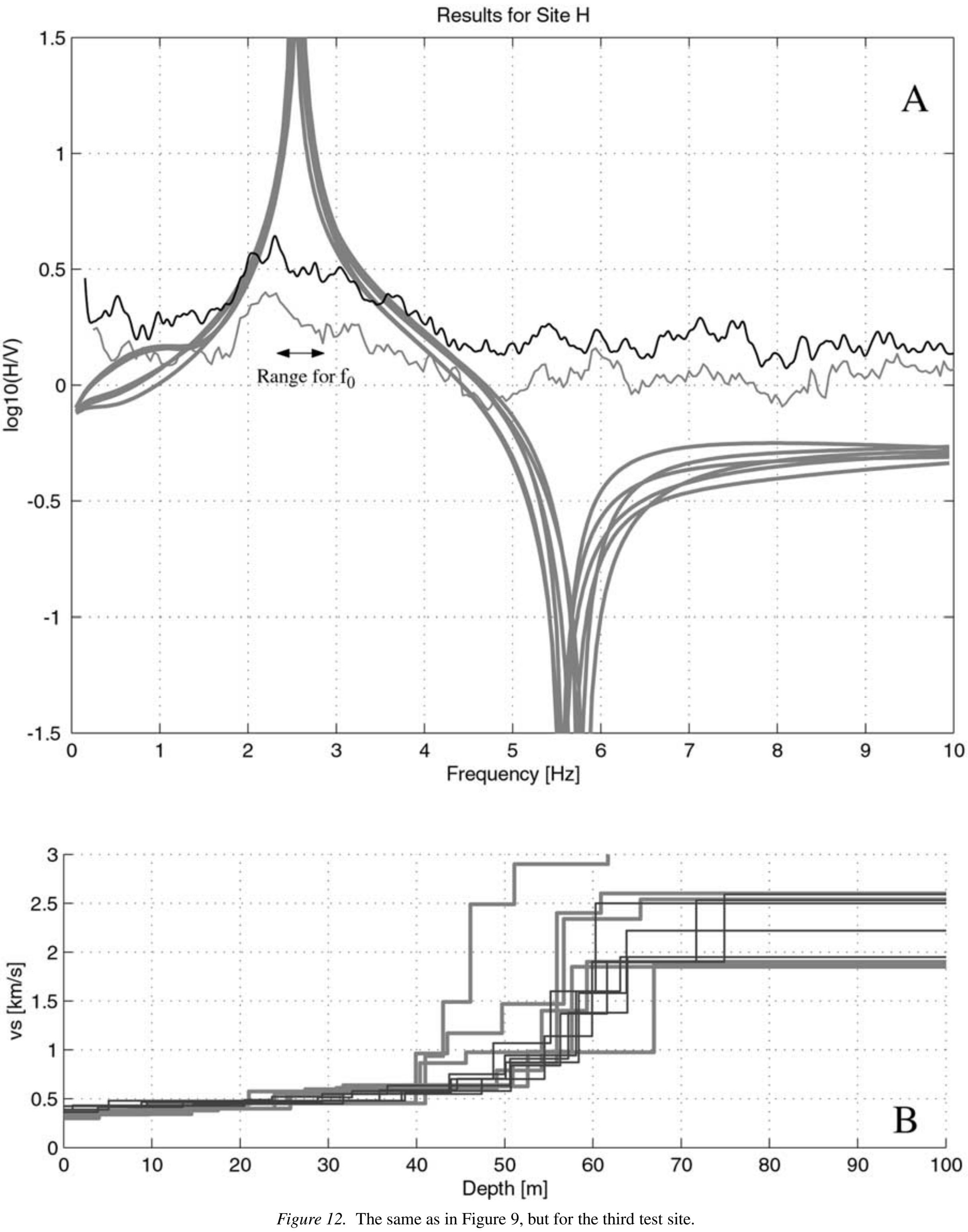

Figure 12. The same as in Figure 9, but for the third test site.

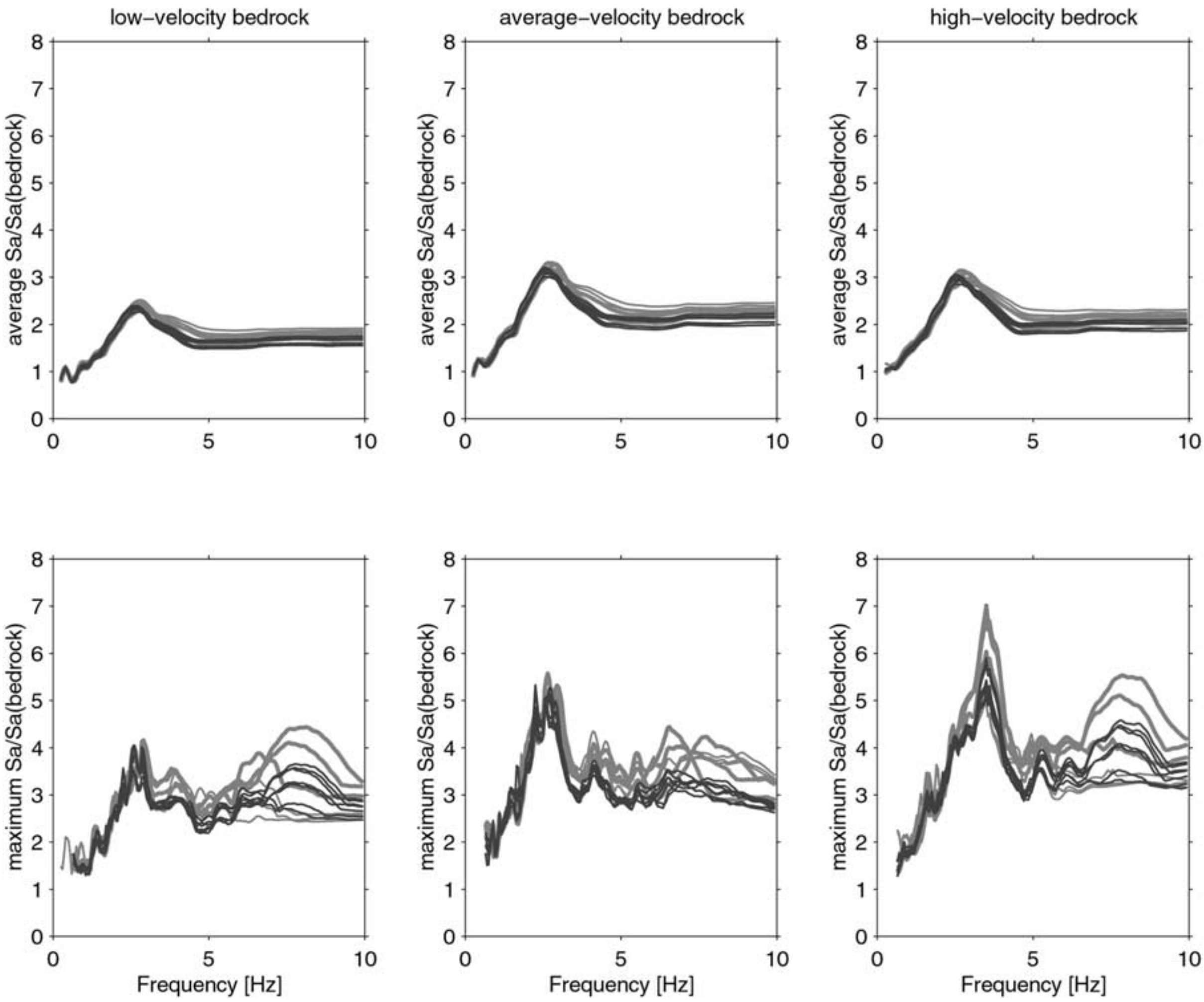

Figure 13. The same as in Figure 11, but for the third test site.

A careful geological investigation of the site is a prerequisite to obtain reasonable S-wave velocity profiles from the proposed inversion scheme. This will also ensure that the investigated peak in the H/V ratio is related to the fundamental mode Rayleigh wave. In structures with two, or maybe three strong impedance contrasts, we can expect to obtain several peaks related to the fundamental and higher modes Rayleigh waves. An application of the H/V spectral ratios to determine S-wave velocity profiles for such structures is not straight-forward and needs further theoretical studies.

The resulting uncertainty in the structure affects the uncertainty of the estimated site-amplification expected during earthquakes. For the inverted models, we therefore computed site response for a large number of events, which allows to define the uncertainty by the apriori unknown source position and mechanism of a future earthquake. In most cases the variability between the results obtained for the different models is much smaller than the variability introduced by the unknown source position. The accuracy with which S-wave velocity structures can be retrieved from observed H/V ratios is therefore sufficient for an application of the method in seismic hazard analysis for a specific site.

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