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S-WAVE VELOCITY PROFILES FROM FULL MICROTREMOR HORIZONTAL-TO-VERTICAL (H/V) SPECTRAL RATIOS INVERSION ONSHORE AND OFFSHORE

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ABSTRACT

Recent theoretical developments in horizontal-to-vertical (H/V) spectral ratio modeling are used to invert the microtremor H/V spectral ratio curves for the shear wave velocity profile at one onshore and one offshore sedimentary site in Switzerland. The H/V forward model uses the seismic interferometry principles under the diffuse field assumption to estimate the imaginary part of the Green's function for collocated source and receiver. At the onshore site at Buochs, the H/V curves are obtained from a strong motion borehole station with three sensors located at surface, 26, and 100 m depth. At Lake Lucerne (offshore Weggis), the H/V curve is estimated from an ocean bottom seismometer station located on the lake floor at 38.1 m water depth. The inversion of real offshore H/V curves is preceded by a synthetic modeling and inversion where a water layer is considered on top of the best model candidate from H/V inversion at Buochs.

Keywords: microtremor H/V ratios, borehole, OBS, site effects, shear wave velocity

INTRODUCTION

The microtremor horizontal-to-vertical (H/V) spectral ratio has emerged as a single-station method in ambient vibration analysis due to its capability to estimate the frequency of resonance at sites with sediment cover overlaying the bedrock (Nakamura, 1989; Bard, 1998). Moreover, using additional constraints from a receiver at depth and sufficiently long recording times, a shear-wave velocity profile can be derived from H/V spectral ratios (Lontsi et al., 2015). Recently, the H/V forward modeling code was generalized to consider offshore environments (Lontsi et al., 2019). Here, we consider these developments and move forward to estimate the shear wave velocity profile both at a strong motion borehole site at Buochs, and at an ocean bottom seismometer (OBS) site in Lake Lucerne (Switzerland).

The borehole station at Buochs (SBUS) was built as part of the Swiss Strong Motion Network renewal project (phase 2) and comprises both accelerometer and pore pressure sensors (Hobiger et al., 2019; 2021). SBUS aims at monitoring the seismic activity in Switzerland and the surrounding areas, and also non-linear site response, especially liquefaction processes during earthquakes.

Lake Lucerne and the surrounding region have experienced a number of seismic events in the past (see earthquake catalogs Fäh et al., 2011; Kremer et al., 2017, 2020) that have caused both subaerial (Schwarz-Zanetti et al., 2003) and subaquatic slope failure (Schnellmann et al., 2002). One example of such an event is the Mw 5.9 1601 AD Unterwalden earthquake that caused tsunamigenic mass-movements (Schnellmann et al., 2003). Between May 2018 and June 2020, we performed OBS measurements at different locations around the lake to assess the internal structure of the subaqueous slopes, where sediments are susceptible to failure or have already failed.

For the analysis of the accelerometer data, we first analyzed the spatio-temporal variability of the estimated microtremor H/V spectral ratio and selected an appropriate H/V spectral ratio curve for the inversion. From the inversion results at Buochs, we perform a synthetic H/V spectral ratio analysis to assess the effects of the water layer on the H/V(z, f) spectral ratio at different depths. For this purpose, a 50 m water column was considered. We further invert the synthetic H/V spectral ratio curves with a constraint from a receiver at depth. The application to real OBS data is conducted for the site offshore Weggis (Lake Lucerne).

SITE LOCATION AND GEOLOGY

Lake Lucerne is a peri-alpine lake of glacial origin situated in Central Switzerland. Fig. 1 gives an overview of the lake, the known areas of slope failure in the past and the locations for our borehole and OBS stations. The lake contains a Quaternary sediment cover on slopes that range from few meters to hundreds of meters (Finckh et al., 1984; Hilbe et al., 2011). The borehole station SBUS is located at Buochs, at about 50 m to the lake shore. The subsurface geology at the borehole station, SBUS, mainly consists of alluvial deposits of the Engelberger Aa. Drill cores show that the superficial layers consist mainly of sand, gravel and silt. At the site, a surface seismometer is installed in a vault about 1 m below the surface. Two borehole sensors are located in two separate boreholes at depths of 26 and 100 m, respectively (Hobiger et al., 2019; 2021).

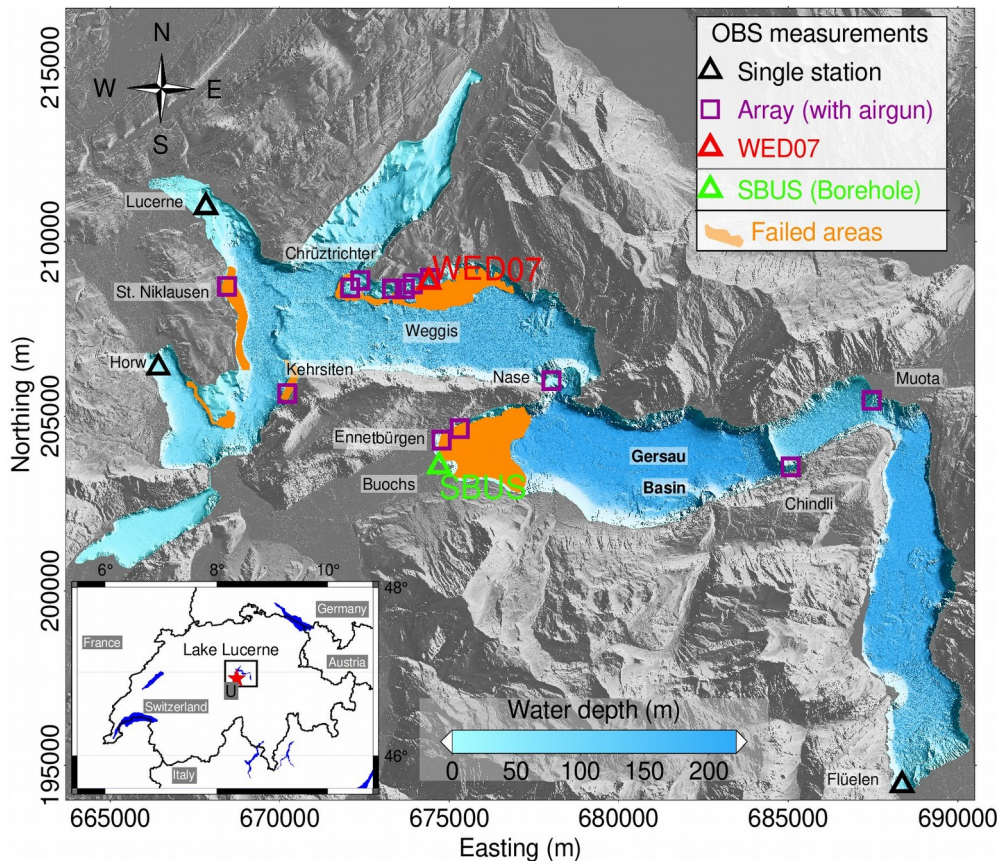


Figure 1: Overview of the OBS measurement sites and the location of the borehole station. The borehole station SBUS is represented by the triangle with green color. The OBS station WED07, that is used in this study, is represented by the red triangle. The background layers represent the bathymetric map of Lake Lucerne (Hilbe and Anselmetti, 2014) and the topography. Patches of failed slopes from past events are shown with orange color (Hilbe and Anselmetti, 2015). The inset indicates the location of Lake Lucerne within Switzerland. The epicenter location of one of the past events, the AD 1601 Unterwalden (U) earthquake, is indicated by the red star on the inset.

S-WAVE VELOCITY PROFILE AT BUOCHS: BOREHOLE SITE

H/V temporal variability at Buochs

We estimate the microtremor H/V spectral ratio from day-long noise recordings at each of the three borehole sensors (SBUS.SF, SBUS.M1, and SBUS.BT). The stations operate continuously since June 2019. The H/V spectral ratio is estimated on windows of 80 s. The total number of time windows contributing to the H/V spectral ratio estimation for each specific day may vary when there are gaps in the original daily data file. Fig. 2 shows all H/V spectral ratio curves for the period from June 2019 to October 2020 and the relative variation of the daily H/V spectral ratios with respect to a reference H/V spectral ratio curve, measured on March 1st, 2020 for the surface station SBUS.SF. The reference curve, which is also the target for the inversion, was selected in such a way that the energy in the deep space (low frequencies), here around 0.2 Hz, is nearly the same on the three components. The H/V spectral ratio shows seasonal variations. One pattern starts from the deployment day in June 2019 to mid-September 2019 and continues from mid-March 2020 to mid-September 2020. Variations for this recording period are observed at frequencies below 1 Hz and between 6 and 9 Hz. The H/V variations in these frequencies are characterized by more than 60 percent decrease in the H/V amplitude with respect to the reference station. The variations can be related to human activities that include for example the use of private boats that are at the site in summer. A strong and isolated variation characterized by a decrease in the H/V amplitude for frequencies below 1 Hz is observed around December 25th, 2019. Two H/V curves from December 24th and 25th, 2019 have the lowest amplitudes for frequencies below 1 Hz on Fig. 2(a) and correspond to these two dates. In addition to the inversion target for the surface station, two additional target curves from March 1st, 2020 were obtained for the borehole stations SBUS.M1 at 26 m depth and SBUS.BT at 100 m depth.

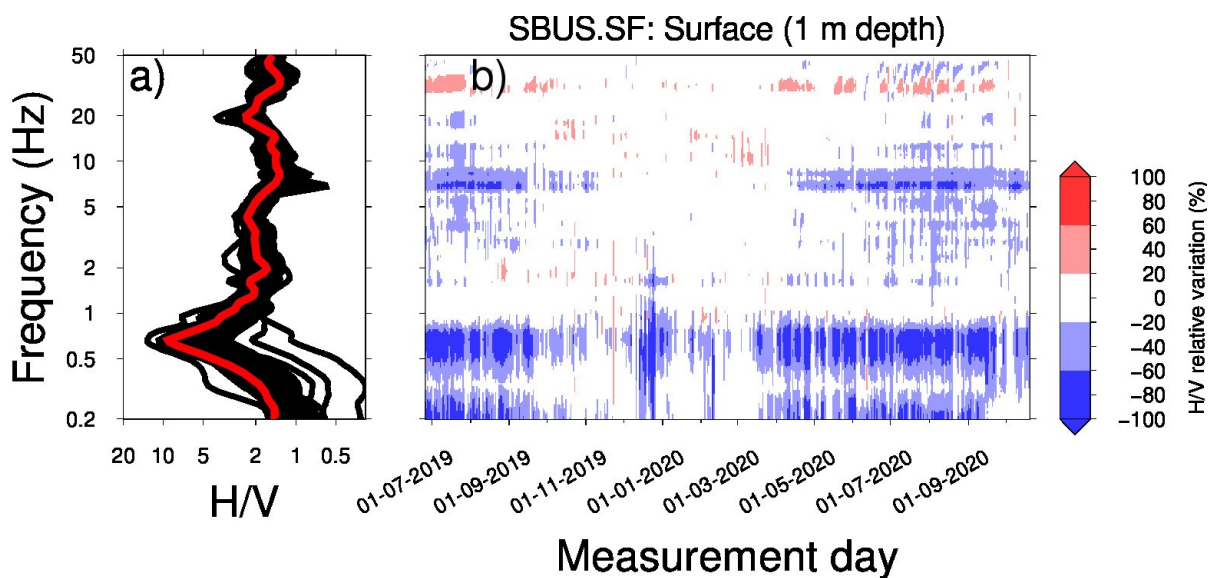


Figure 2: Microtremor H/V spectral ratio temporal variation at Buochs. a) All H/V spectral ratio curves for the station SBUS.SF. The reference H/V spectral ratio curve for variation analysis was measured on March 1st and is shown in red. b) Relative variations of the H/V spectral ratio curves. SF stands for the location code for the surface station.

Full microtremor H/V(z, f) inversion at Buochs

We assume that the 1D assumption is valid for the considered wavelength range and parameterize the subsurface by a stack of six homogeneous layers over a half space. The search range for the S-wave in each layer was defined with sufficient liberty, but realistic values, in order to allow the inversion

algorithm to find the best set of models that are representative of the subsurface at Buochs. The results of the inversion are given in Fig. 3 for all models with combined misfit values lower than 1.

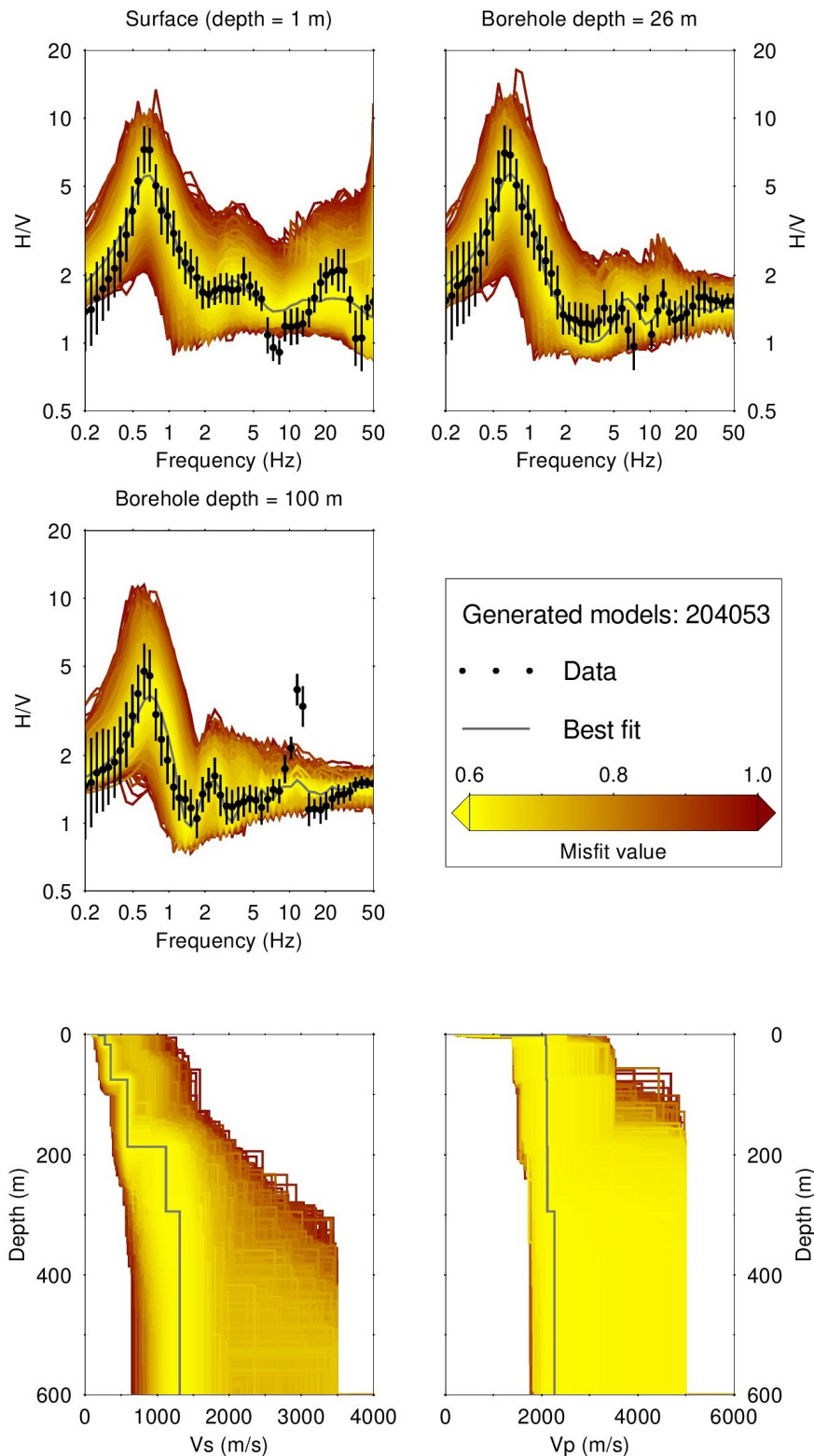


Figure 3: Full microtremor H/V spectral ratio inversion results at the borehole station at Buochs (SBUS). The first three panels show the inversion results for the receiver at the surface, at 26 and 100 m depth. Below, the S-wave and P-wave velocity profiles are shown. All models with misfit below 1 are included. The dotted line indicates the target H/V spectral ratio curve with the corresponding error. The continuous gray curve indicates the best fit.

For the best model, characterized by the lowest misfit value, the overall sediment cover is 187 m. The V_s values are 184 m/s at the surface and 584 m/s at 187 m depth. We also present the P-wave velocity information, but do not make any interpretation because the Poisson ratio was weakly constrained.

The H/V spectral ratio curves are well retrieved in the frequency range from 0.2 to 7 Hz for all sensors. The best model for the surface sensor follows the data curve above 7 Hz and shows slight differences in the amplitude. The sensor at 26 m depth shows a stable behavior for the H/V spectral ratio amplitude on the analyzed frequency range. The borehole sensor at 100 m has an H/V spectral ratio that exhibits a large amplitude observed at about 12 Hz. This large amplitude does not appear on the two shallow borehole sensors and is probably artificial. This explains the discrepancy between the data and modeled curves at this borehole sensor.

H/V SPECTRAL RATIO OFFSHORE: SYNTHETIC ANALYSIS

Forward calculation

We consider the best model candidate from the inversion at Buochs and assess the effects of the presence of a water layer on top on the H/V spectral ratio. The water layer is defined by the compressional wave velocity, the density, and the water thickness. The elastic layers are defined by the compressional and shear wave velocities, the density, and the layer thickness. Four receivers are considered for the synthetic analysis and are located at the bottom of the water layer, and at depths H1, H2, and H3 as illustrated by Fig. 4 (top). For the H/V calculation, the following values are used: $h = 50$ m, $H1 = 4$ m, $H2 = 12$ m, and $H3 = 187$ m. The results of the forward calculation, including a scenario without water layer are plotted together for comparison (Fig. 4). We observe variations in the H/V spectral ratio amplitude for frequencies around and above 0.65 Hz, the peak frequency. The peak frequency remains unchanged. H/V curves for depths at the lake floor H1, and H2 differ in amplitude for frequencies above 1.5 Hz. The H/V calculation on top of the bedrock depth $H3 = 187$ m shows no large amplitude on the H/V spectral ratio curve, as expected.

Synthetic inversion

A synthetic inversion is performed by combining the H/V spectral ratio curves for the receivers at the lake floor (50 m below lake surface) and at 62 m equivalent to $H2 = 12$ m. A synthetic noise equivalent to 20 percent of the H/V spectral ratio amplitude at a given frequency is added to the synthetic H/V data curve. The inversion results are shown in Fig. 5. There is a very good fitting between the synthetic data and the best fitting curve. The S-wave velocity profile is well retrieved. The P-wave velocity is also well retrieved, although the latter case has a lower sensitivity.

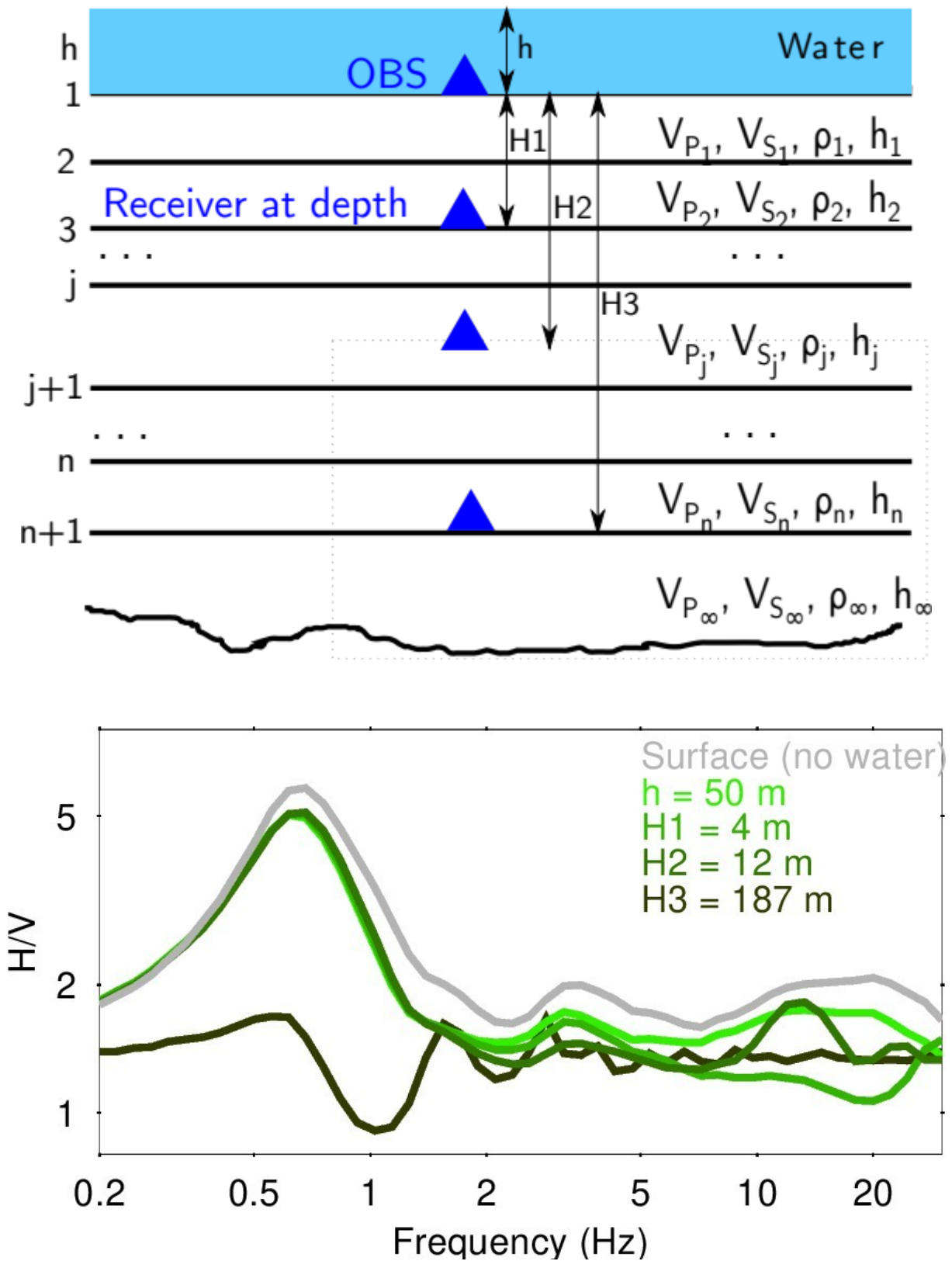


Figure 4. Top: Schematic representation of a layered subsurface structure with a water layer on top. Sensor locations are considered at depths $H1$, $H2$, and $H3$ below the water layer. Bottom: Synthetic H/V spectral ratio curves for receivers located at the bottom of the water layer, at $H1 = 4$ m, $H2 = 12$ m, and $H3 = 187$ m. The H/V curve in the absence of a water layer is shown in gray.

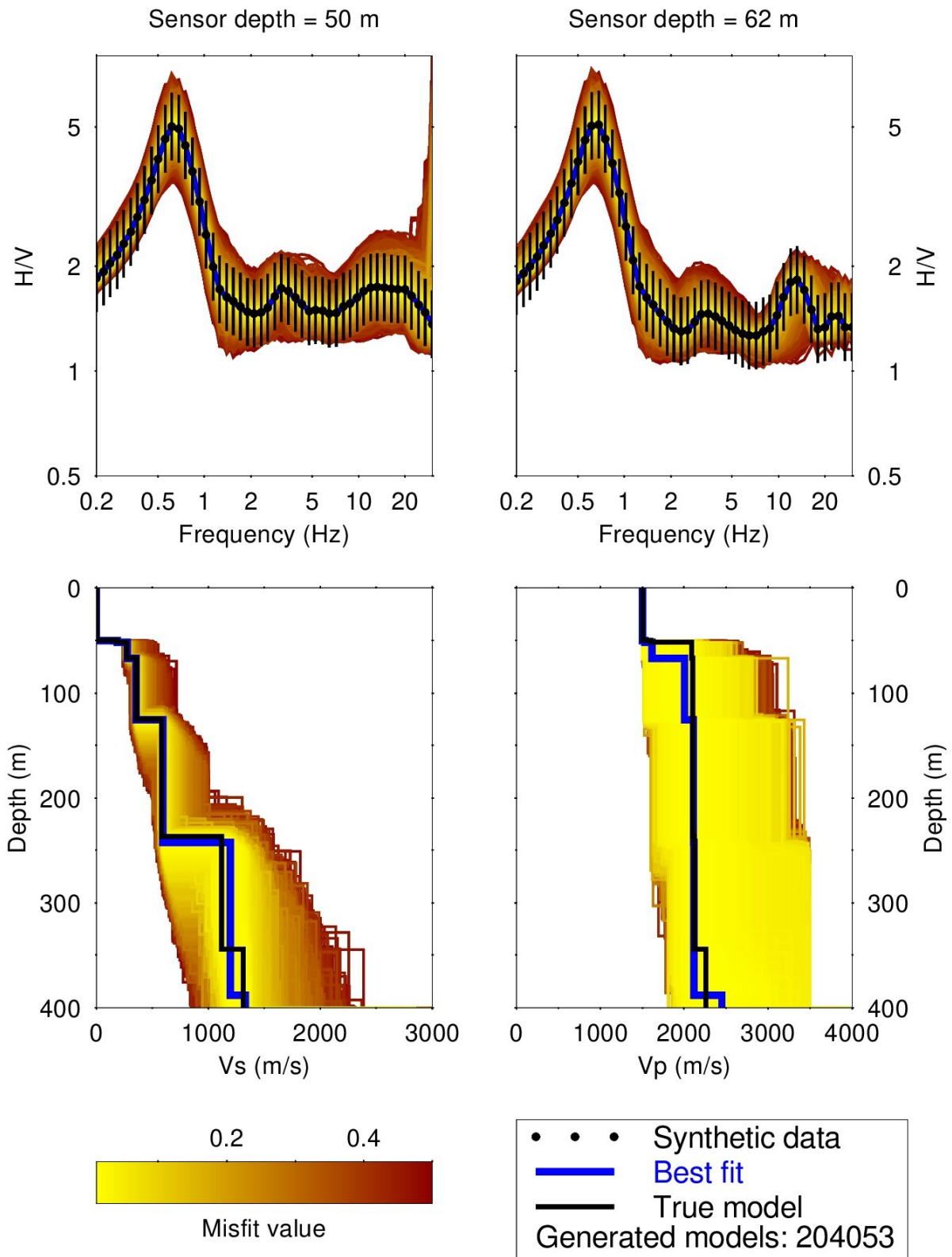


Figure 5. Top: Synthetic H/V spectral ratio inversion offshore for the receivers at the bottom of the water layer and at $H_2 = 12$ m. The vertical bars indicate the error. The error is set to 20 percent of the synthetic $H/V(z, f)$ spectral ratio amplitude. Bottom: Obtained velocity profiles.

APPLICATION FOR S-WAVE VELOCITY PROFILE AT WEGGIS (LAKE LUCERNE): OCEAN BOTTOM SEISMOMETER SITE

Fig. 5 shows the H/V spectral ratio inversion results for one OBS station, WED07, at Weggis. The site is characterized by a water column of 38.1 m. This depth corresponds to the location of WED07. The H/V spectral ratio at this site presents a relatively complex structure and is characterized by a very broad peak between approximately 1 and 4 Hz. Even if we know that the H/V ratio as a unitless ratio suffers in an inversion to uniquely estimate the absolute values of the shear-wave velocity profile, we attempted an inversion for the offshore H/V spectral ratio curves where we currently do not have measurement at depth. The preliminary inversion results are shown in Fig. 6. Obviously, the code is able to fit the measurements. Nevertheless, in order to obtain reliable shear wave velocity profile, the inversion would be much better constrained by adding for example H/V spectral ratio measured at depth, phase velocity dispersion curves obtained by array analysis (Shynkarenko et al., 2021), or layer thicknesses from seismic surveys.

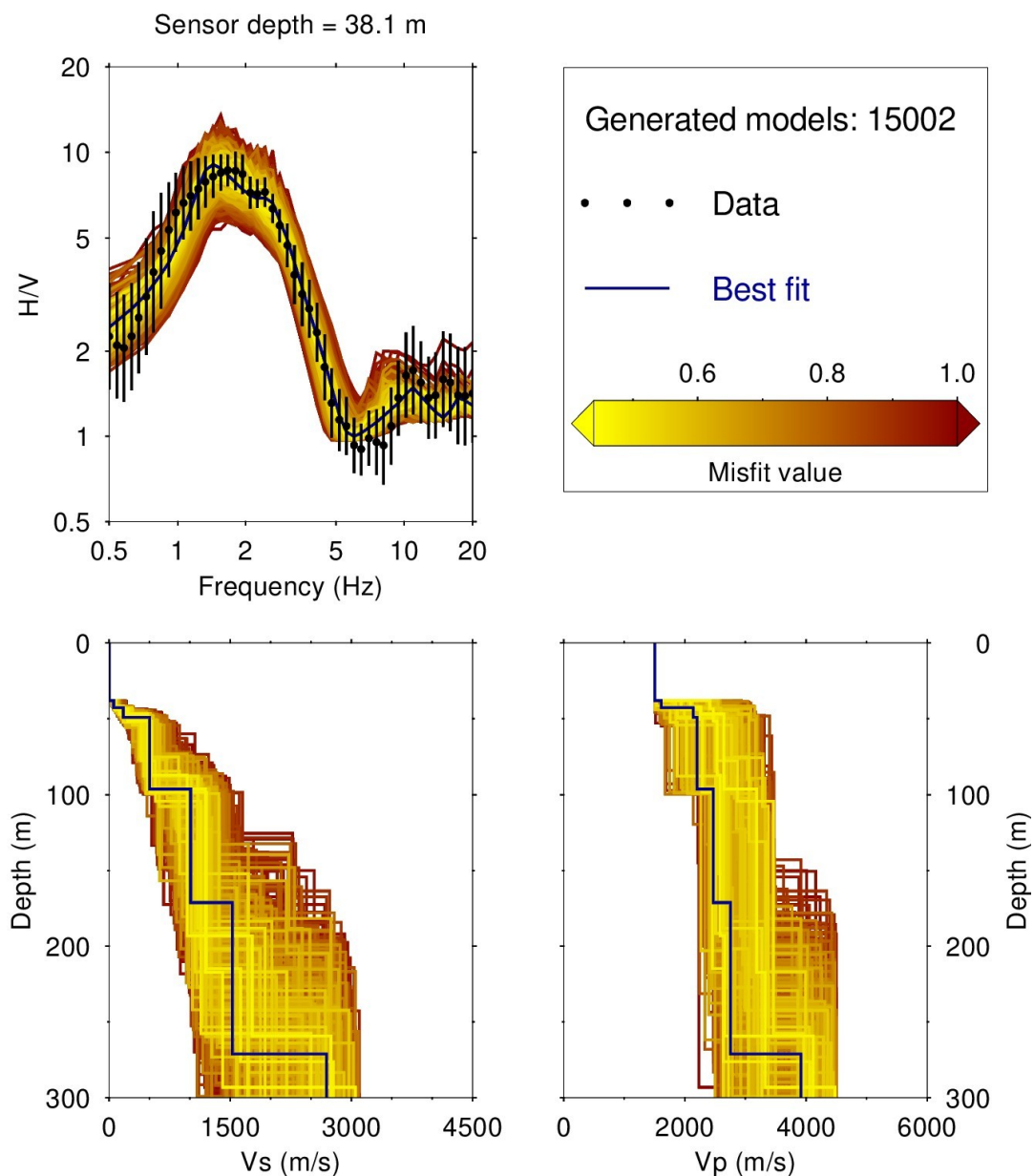


Figure 6. H/V inversion results for the OBS station WED07 at Weggis.

CONCLUSION

The continuous recording of ambient vibration data over months has provided a framework to assess the temporal variability and reliability of the microtremor H/V spectral ratio from the accelerometer at the strong motion borehole site at Buochs. We observe strong variations in the H/V spectral ratio from the accelerometer reaching a factor of 2. Despite this amplitude variation that can be linked to seasonal variability, there is consistency in the observed H/V spectral ratio curves. The inversion of the H/V spectral ratios from the accelerometer have provided information about the S-wave velocity profile for SBUS.

A synthetic analysis was performed to first assess the effects of the presence of the water layer on the H/V spectral ratio, and second to test the capability of the inversion algorithm to retrieve seismic velocity profile information. By ignoring any disturbances that are encountered in the ambient noise measurement offshore, such as gravity waves, we observed that for the considered model, the presence of the water layer has some non-negligible effects on the amplitude of the H/V spectral ratio curve. The synthetic inversion that takes into account the receivers at depth was able to retrieve the starting model up to some minor deviations. The preliminary inversion results of real H/V data from OBS shows good results at Weggis. However, the inversion is not constrained and the results will be much more reliable if additional information are used which fix the absolute values of the shear wave velocity profile at some depths. For this purpose, the H/V measured at depth and the phase velocity dispersion curves from the analysis of the OBS array data will be included in the future. Also the structure investigation will be extended to all OBS deployment sites.

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