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ON THE POTENTIAL OF MICROTREMOR MEASUREMENTS

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SUMMARY

The spectral features and polarization of microtremors exhibit a gross correlation with the site geological condition. This question is addressed in our contribution by use of one- and two-dimensional numerical modeling in combination with field measurements. Synthetics are used to derive relations between the amplitude of the H/V ratio, the S-wave velocity and Poisson’s ratio of the sediments. The theoretical results are then compared with the results from field measurements. The sites of interest have been investigated through borehole information and geophysical prospecting. The effect of two-dimensional structures is analyzed and related to results obtained from a reference site technique. Two examples are presented: a deep graben structure in the Basel area and the moraine of the Rossboden glacier in the Swiss Alps.

INTRODUCTION

Microtremor methods have long been used extensively in Japan, and much less in other parts of the world, due to some questions that were not satisfactorily answered. The Nakamura version of the microtremor methods has proved to be one of the most convenient techniques to estimate fundamental frequencies of soft deposits [e.g. Lermo and Chavez-Garcia, 1994; Lachet and Bard, 1994; Fäh et al., 1997]. It has been shown by several authors that there is no straightforward relation between the H/V peak amplitude and site amplification. However, the peak amplitude of the H/V ratio is affected by the characteristics of the unconsolidated soils and the underlying bedrock.

Ambient noise measurements can be used to recognize thick layers of unconsolidated soils, which are not resolved by borehole data [e.g. Fäh et al. 1997]. While polarization spectra are a useful tool for estimating the fundamental resonance frequency of the soft soils, the ratio is inadequate in estimating ground-motion amplification especially in deep sedimentary basins [Lachet and Bard, 1994; Dravinski et al., 1996]. Therefore, a two step procedure is required to estimate amplification effects. The first step involves the determination of the structure of the local site with the uncertainties in the soil parameters. The second requires the estimation of amplification effects at the local site.

THEORETICAL BACKGROUND

The horizontal to vertical spectral ratio (HVSR) method was developed in Japan and first published in English by Nakamura (1989). Several studies have been done about the interpretation of these polarization spectra [e.g. Lermo and Chavez-Garcia, 1994; Lachet and Bard, 1994; Fäh et al., 1997] and the interpretation of its first peak as fundamental frequency of resonance of the local ground is commonly accepted.

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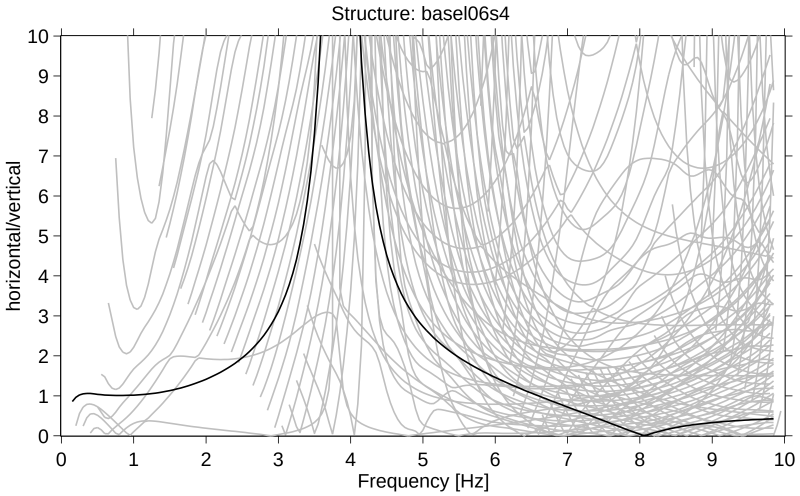

Figure 1. Polarization of all normal modes that exist in a given structural model. The fundamental-mode Rayleigh wave is plotted as a black solid line whereas all other modes are shown in gray.

The physics of the polarization of waves (H/V ratio) can be explained with the ellipticity of the normal modes in the P-SV case. An example is given is Figure 1 for a structure composed of an average layered crustal model for the Basel area covered with a layer of unconsolidated sediments (h=24 m, vp=1350 m/s, Qa=50, vs=400 m/s, Qb=20) [Fäh et al., 1997]. The numerical method for high-frequency P-SV waves, used to compute this polarization spectrum, was proposed by Panza [1985]. The set of normal modes is complete for a given phase velocity band (0 - 4670 m/s) and frequency band (0.05-10.0 Hz). The polarization of the fundamental-mode Rayleigh wave is plotted as a black solid line, whereas all other modes are shown in gray. In general, energy from all modes of Rayleigh waves can contribute to the ambient noise. The curves of the theoretical polarization spectra are all polarized at the fundamental frequency of resonance of the soils at about 4.1 Hz. This is not always observed in the theoretical polarization spectra, especially for structures with a small shear-wave velocity contrast between unconsolidated sediments and bedrock. SH-waves contribute to the horizontal wavefield in the observed ambient-noise. These SH-waves shift the measured average polarization spectrum towards higher values. The amplification of SH-waves at the resonance frequency may cause an additional stretching of the spectrum at the fundamental frequency of resonance.

The most important parameters when considering the H/V ratio are the shear-wave velocity contrast between sediments and bedrock, the geometry of the interface between bedrock and sediments, and the shear-wave velocity of the unconsolidated sediments. Other factors of influence are the distance from the noise sources and their depths, the velocity gradient and the Poisson's ratio in the soft sediments.

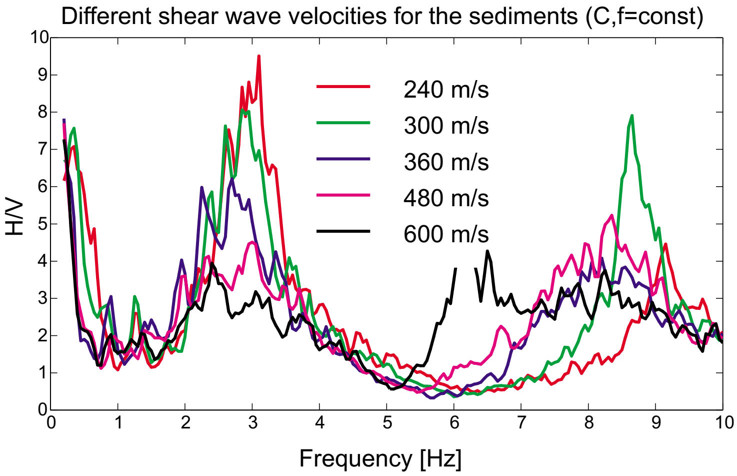

Figure 2. H/V ratio obtained for different shear-wave velocities of the unconsolidated soils, by assuming a one-dimensional structure.

An example is given in Figure 2 to show the effect of the shear-wave velocity of the unconsolidated sediments on the H/V ratio. Numerical simulations are performed with a finite difference technique. Varying the thickness of the sedimentary layer linearly with its shear wave velocity, so as to keep the fundamental frequency of resonance f0 of the model structure, and also fixing the velocity in the bedrock layer, we can study the influence of the shear wave velocity contrast on the shape of the polarization curve. Clearly the main peaks vary greatly in shape and amplitude, which gives an impression of the possible potential of microtremor measurements in analysing and identifying subsurface conditions.

In the case of a two-dimensional structure, different patterns can be observed: the antiplane shear modes, corresponding to the SH motion; the in-plane shear modes (SV); and the in-plane bulk modes (P) [Bard and Bouchon, 1985]. Each of them is characterized by different peak frequencies. The resonance modes depend on the shape of the basin, the velocity contrast between bedrock and sediments, the Poisson's ratio and damping of the sediments. Depending on the local structure, different modes can have the potential for amplification, are easily excited, and therefore dominate the observed H/V ratio. An important factor is also the type and location of the sources that excite the ambient-noise wavefield. The two-dimensional resonance frequencies and the amplification values differ significantly from the one-dimensional case.

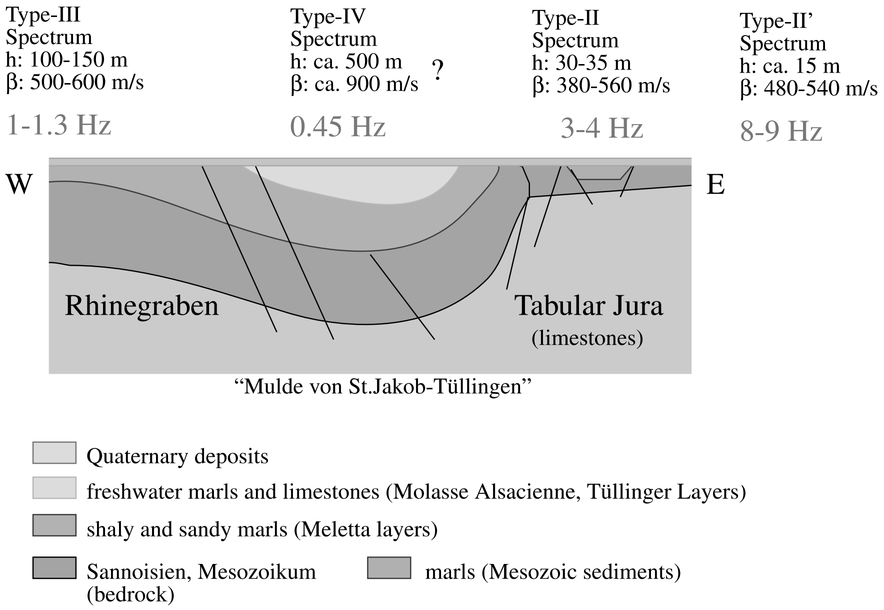

Figure 3. Cross-section through the Basel area indicating the approximate fundamental frequency of resonance and the shear-wave velocities of the unconsolidated sediments estimated by Fäh et al.[1997].

MEASUREMENT AND INTERPRETATION OF AMBIENT NOISE FOR 1D-STRUCTURES

Our present study area is the city of Basel in Switzerland. Due to different site conditions and the availability of data about numerous boreholes, it constitutes an ideal test site for microtremor techniques. Figure 3 shows an east-west cross-section through the area. The area is close to the eastern master fault of the southern Rhinegraben. The throw at the border fault of the Rhinegraben is about 1400m. Within the Rhinegraben (on the downthrown side) the Mesozoic strata (Triassic to Jurassic) are covered by 500 to 1000 m of Tertiary sediments. They form an asymmetric syncline with its axis parallel to the fault zone forming the "Mulde von St. Jakob – Tüllingen" [Fischer et al., 1971; Gürler et al., 1987]. These Tertiary layers are known only by very few outcrops and deep reaching wells. The following Tertiary formations can be distinguished: The mostly argillaceous marls of the Meletta layers (max. 350 m thick), which become more sandy at its transition to the "Molasse Alsacienne". The "Molasse Alsacienne" with a maximum thickness of 300 m is an intercalation of sandy layers and argillaceous marls. The topmost "Tüllinger Süsswasserschichten" (max. 200 m thick) are calcareous to argillaceous marls with interlayering of freshwater carbonates. At their base gypsum is frequent. Carbonates are found predominantly in the northern part, whereas the marly facies is more developed to the south.

Above the Tertiary sediments 5 to 40 m of Pleistocene and Holocene gravels were deposited, mostly by the river Rhine. The composition of these gravels is well known throughout the urban area by about 3000 shallow wells, which were drilled for construction and groundwater purposes (Noack, 1993). To the east, on the shoulder of the Rhinegraben, the Mesozoic sediments of the Tabular Jura [e.g. Laubscher, 1982] are covered directly by 5 to 50 m of Pleistocene and Holocene gravels, and in some parts with an additional layer of marls.

In order to obtain the fundamental frequency of resonance and its variation within the area of interest, a campaign of systematic ambient noise measurements has been carried out, involving over 250 measurements (Kind et al., 1999). The measurement points have been selected to give a good coverage of the model area, a large selection of different quaternary sediments and sediment thicknesses, and a good coverage of the prequaternary geological structures. All measurements were made at or close by the site of a shallow borehole, where the depth and a geotechnical description of the local quaternary sediments was available. From this ambient noise data set we are able to map the fundamental frequency of resonance in the Basel area, which is shown in Figure 4.

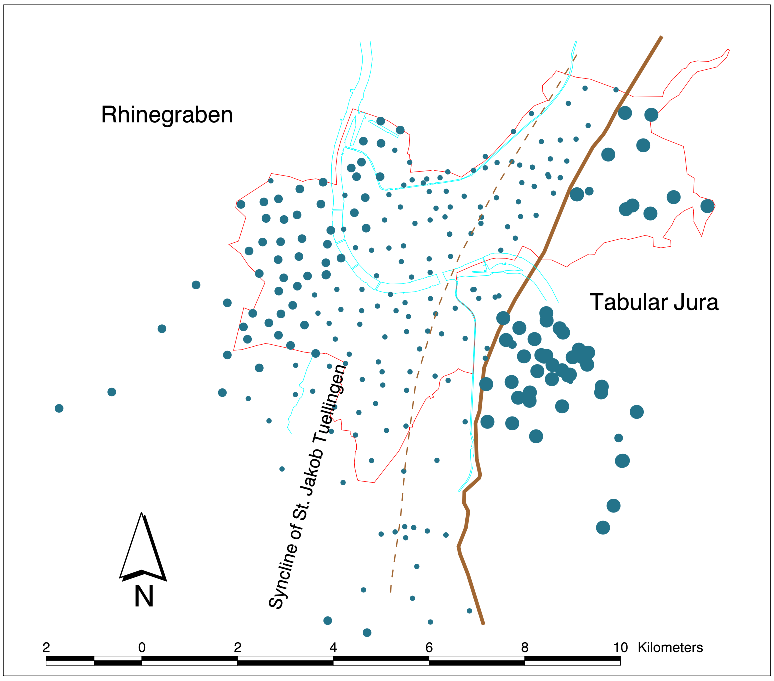

Figure 4. Ambient noise measurements: Drawn are the city limits of Basel, the rivers and the flexural monocline of the Upper Rhine Graben. Large points indicate a fundamental frequency higher than 2Hz, medium points are in the range of 0.75-1.2Hz and the small points represent frequencies of 0.3-0.75Hz.

Clearly, the main geological structure is reflected in the measurement results: The flexural monocline of the Upper Rhine Graben separates the measurements in two distinct areas. In the eastern part, quaternary gravels over the Tabular Jura show a strong contrast and cause the main peak. West of the Flexural Monocline the softer prequaternary below the gravels show up in the peak as well. In the Rhine Graben the division in the deeper syncline of St. Jakob Tüllingen and the less deep area further to the west are also visible.

But the use of the ambient noise measurements is not limited to the interpretation of the first peak. In many places in the Rhinegraben, further peaks can be seen at higher frequencies, which can be explained by the resonance modes of the quaternary layer. As there is an abundance of boreholes in the Basel area giving detailed geotechnical information about the quaternary sediments, a combination of several methods can be used to infer seismic properties for the structure.

A first analysis of the data for peaks representing quaternary sediments was conducted. To identify polarization peaks of that origin, the formula for the fundamental frequency of resonance of a single soft layer over a halfspace was used together with the possible shear-wave velocity range (150-900m/s) and the depth of the quaternary sediments. This resulted in 114 measurement points, where such a peak could be identified, including only measurements which are closer than 25m from a borehole.

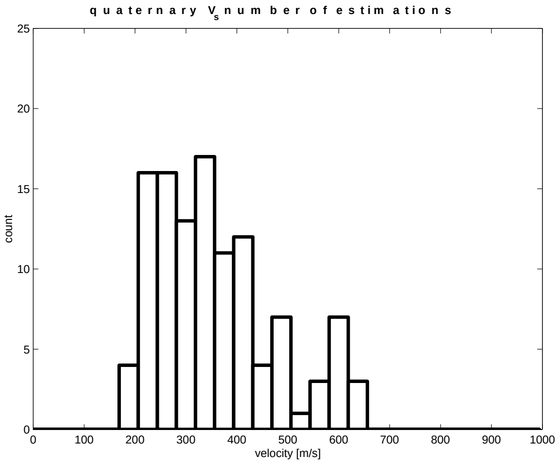

Figure 5. Overview of the estimated shear wave velocities from the polarization analysis of ambient noise.

With this data set, we get shear wave velocity estimations for the quaternary sediments. The resulting values are shown in Figure 5 in the form of a histogram. From this figure we grouped the measurements in three classes; estimates of less than 300m/s, between 300 and 450m/s and higher than 450m/s. They would represent types having average velocities of 230, 360 and 530m/s, as can be seen from Figure 6. This approach can be used to geophysically classify the quaternary deposits.

The resulting values are low when compared to values derived from standard penetration tests (SPT). The reason for this difference lies in the uncertainty of the depth of the actual velocity contrast causing the peak. Since the prequaternary material is altered at its upper interface by weathering processes and the ground water, the actual depth of the soft layer is greater than the depth of the quaternary sediments. As a consequence we get an underestimation of the shear wave velocity from this simple estimate. It represents a lower limit, which is very useful when velocity ranges have to be defined in the future microzonation study. The accumulated dataset is subject to our present research and will certainly provide many important results.

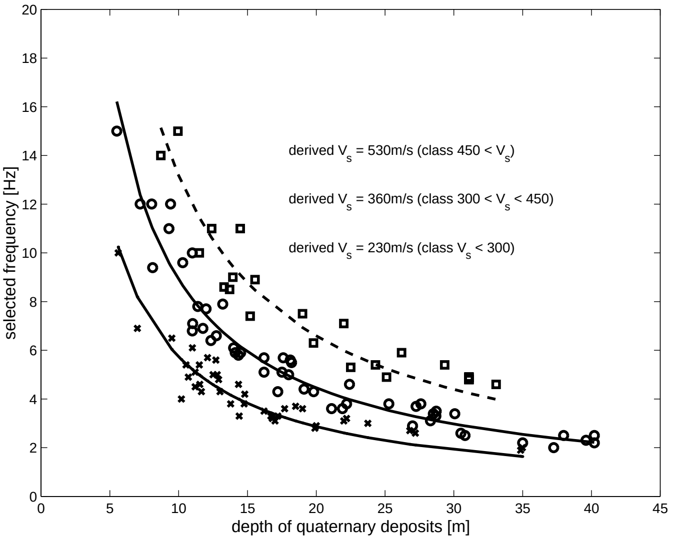

Figure 6.Fundamental-mode resonance frequency of quaternary sediments versus thickness of the sediments. The measurements have been divided in three groups from the velocity distribution, resulting in soil types with average shear wave velocities of 230, 360 and 530 m/s respectively.

MEASUREMENT AND INTERPRETATION OF AMBIENT NOISE FOR 2D-STRUCTURES

It has been recognized that within the syncline of St. Jakob Tüllingen there is almost no variation of the fundamental frequency of resonance [Fäh et al., 1997], which indicates a two-dimensional resonance effect. For this reason an experiment was performed for this area that consisted in a series of numerical 2D simulations (SH-and P-SV case) as well as a field experiment [Steimen, 1999; Steimen et al., 1999]. These experiments showed that the fundamental in-plane shear mode (SV00) can be well excited by incoming waves in the frequency range between 0.30 and 0.32 Hz. The fundamental mode SH waves can not be excited, whereas its first higher mode SH01 showed the largest amplitudes of all numerical experiments.

The microtremor ground motion were interpreted with the H/V ratio and the reference-site technique. Table 1 summarizes the results obtained from the field measurements and from numerical simulations. For the simulations a model was derived from the geological and geophysical data for the area. Good correspondence of the frequencies of resonance from synthetics and from observations was obtained. Not all modes of resonance are excited. Well excited modes are SV00, SH01, and some higher modes. The first higher, antiplane shear mode SH01 induced a large amplification and therefore dominate the observed H/V ratio.

Table 1. Comparison between the measured and modeled frequency of resonance of different modes.

Mode	*Measurement reference-site [Hz]*	*Measurement H/V ratio [Hz]*	*Modelling reference-site [Hz]*	*Modelling H/V ratio [Hz]*
SV_{00}	*0.30-0.31*	-	*0.30-0.32*	*0.31*
SH_{01}	*0.39*	*0.39*	*0.37*	-
higher SV	*0.44-0.45*	*0.49*	*0.46-0.54*	*0.45*
SH_{06}	*0.70-0.73*	-	*0.70*	-
higher P	*0.91*	-	-	-

The second series of microtremor measurements have been performed at different sites in the symmetry axes of the moraine of the Rossboden Glacier in Switzerland [Salami and Oberholzer, 1998]. The main task was the comparison between H/V ratios of ambient noise and the local structure along the moraine. To investigate the ice-conditions and debris of this moraine several geophysical methods where combined. This included refraction seismics to determine the seismic velocity structure, geoelectric sounding and temperature measurements to evaluate possible permafrost and ice bodies, georadar to investigate glacier thickness and extend, and photogrammetry with air photographs since 1980.

Both the internal structure of the moraine and the distribution of buried glacier ice were determined. The moraine dam consists of dry, moderately consolidated sediments underneath a weathered surface layer. Up towards the active glacier tongue, there are dead ice, watersaturated sediments and ice-debris-mixture under coarse debris. No permafrost was found in the surveyed area. These strongly varying site conditions were efficiently recognized in the H/V ratio measurements (Table 2). On the basis of typical polarization spectra, and by assuming a sinus-shaped form of the moraine, the thickness and degree of consolidation of the debris could be estimated at the different sites along the moraine.

Table 2. Comparison between H/V ratios of ambient noise and the local structures on the moraine of the Rossboden Glacier.

Point Nr.	f0 [Hz]	$\frac{(H/V)_{max}}{(H/V)_{const}}$	β [m/s] estimated	soil conditions
1, 2, 4, 5	1.8 – 2.1	2.2 – 3.7	600 – 650	consolidated moraine
2	0.85	2.9	300	moraine with coarse debris at the
6	2.2	1.7	650 – 700	dead ice covered by a layer with
7, 8, 9	0.85 – 1.5	4.2 – 5.1	250 – 500	unconsolidated moraine
10, 11, 12	2.1 – 2.2	2.1 – 3.2	650 - 700	ice with debris ice mixture
13, 14		~ 1.4 – 1.6		bedrock

Microtremor methods are of special interest due to their low costs and the possibility to apply them in urban areas. Future research will certainly bring improvements in the interpretation of microtremor data and developments of new field techniques.

ACKNOWLEDGEMENTS

This work has been supported by the Swiss Federal Institute of Technology. We thank the Seismology Group of the Trieste University for the use of the spectral part of the Rayleigh waves program.

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ENGINEERING SEISMOLOGY, Microtremor measurement, Numerical modelling, Velocity structure,