



## **EVALUATING SITE EFFECTS IN AREAS OF LOW SEISMICITY**

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### **SUMMARY**

Numerous methods have been developed to evaluate site effects during strong earthquakes. In areas of low to moderate seismicity, no strong motion recordings are available and site effect studies must rely on weak motion records and numerical modeling. Numerical modeling requires good knowledge of the geophysical structure, and needs cheap and fast methods to measure important physical parameters. Ambient vibration techniques have therefore become very important: they provide information on the eigen-vibrations of the geological structure and estimates of S-wave-velocities as a function of depth. This presentation will give examples of work done in Switzerland on site-specific hazard studies, site characterization of seismic stations, and possible applications for building codes.

### **1. SEISMIC HAZARD AND RISK IN SWITZERLAND**

Switzerland is an area of moderate seismicity (Figure 1). Several strong events with magnitude 6 or larger occurred in the past: the Basel earthquake of 1356 (Mw=6.5-6.9), the events of Brig 1755 (Mw=6.1), Visp 1855 (Mw=6.4) and Sion/Sierre 1946 (Mw=6.1) all in the Valais; the 1295 Churwalden event (Mw=6.5) in eastern Switzerland; and the 1601 quake at Unterwalden (Mw=6.2) in central Switzerland. In total, 177 events are known today that reached intensity VI, and therefore caused damage (Fäh et al., 2003b). Recently historical information on effects of these significant earthquakes has been collected and analysed to provide damage patterns of individual large events (e.g. Fritsche et al., 2006a; 2006b; Gisler et al., 2003; 2004; Schwarz et al., 2003; 2004). The work showed that for some events identifiable site effects led to significantly increased damage. While historical cities and villages had been built on sites with good quality soil conditions, the situation has changed during the last century.

Large Alpine valleys with their wide plains of large fluvial and lacustrine deposits or lakeshores and estuaries with water saturated lake deposits show particularly unfavorable soil conditions. Local amplifications of the ground motion and non-linear effects are likely in such places during earthquakes. Due to river regulations and progress in engineering in the last two centuries, these seismically unfavorable sites became, attractive for expanded settlement and industries. For about a century, many villages and cities grew extensively into these plains, as in the Rhine Valley or the Valais, or at Lake sites such as Lucerne, Yverdon and other places. The risk of settlements under this kind of development is thus increasing. Figure 2 illustrates such expansion for the village of Visp in the Valais, a site severely damaged during the 1855 Mw=6.4 earthquake. Figure 3 overviews the damage there together with observed secondary phenomena (Fritsche et al., 2006a). Due to widespread liquefaction, subsidence and lateral spreading of material in the undeveloped river plain, the government in 1855 discussed a motion whether further construction should be forbidden but these issues were forgotten in the decades that followed.

Given the spread of cities and villages into areas of unfavorable soils in many places, future earthquakes will cause more damage than was observed in the past. For this reason it is important to recognize and map possibly affected areas, estimate ground motion and non-linear behavior for engineers and planners, and provide adequate estimates for the building code. This is the objective of seismic microzonation studies, which should map shear-

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wave velocity profiles down to and into the bedrock, the geometry of the deposit (thickness, variability, topography), and the possible occurrence of strong non-linear effects such as liquefaction and landslides. These measured parameters are then used to construct realistic structural models for predicting earthquake ground motion with numerical modelling techniques. Along with observations of earthquake ground motion from seismic networks, such modelling is the basis for defining local seismic hazard.

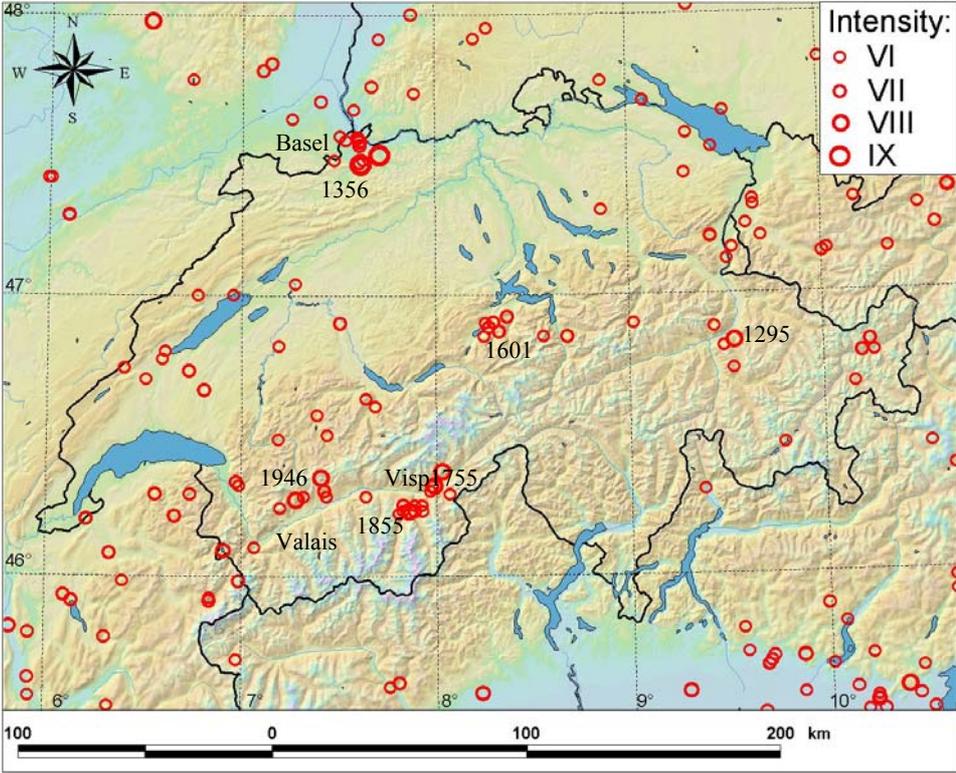


Figure 1: Earthquakes that produced damage, extracted from the Earthquake Catalogue Of Switzerland ECOS (Fäh et al., 2003).

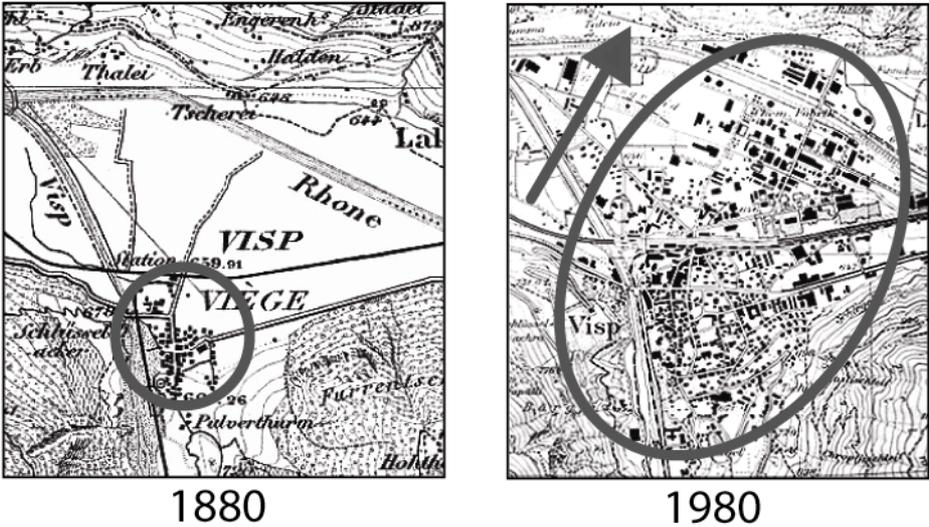


Figure 2: Development of the village of Visp over the last two centuries. The village developed into the river plain of the Rhone, where thick layers of water-saturated sands can be found. This layer liquefied during past earthquakes in the Valais.

Numerical modeling requires good knowledge of geophysical structure, and needs cheap and fast methods to measure important physical parameters. Ambient vibration techniques have therefore become very important in clarifying the eigen-vibrations of the unconsolidated sediments and estimating S-wave-velocities as a function of depth (e.g. Bard, 1998; Bonnefoy-Claudet et al., 2006). Different examples are shown below that illustrate applications of such techniques to different areas in Switzerland.

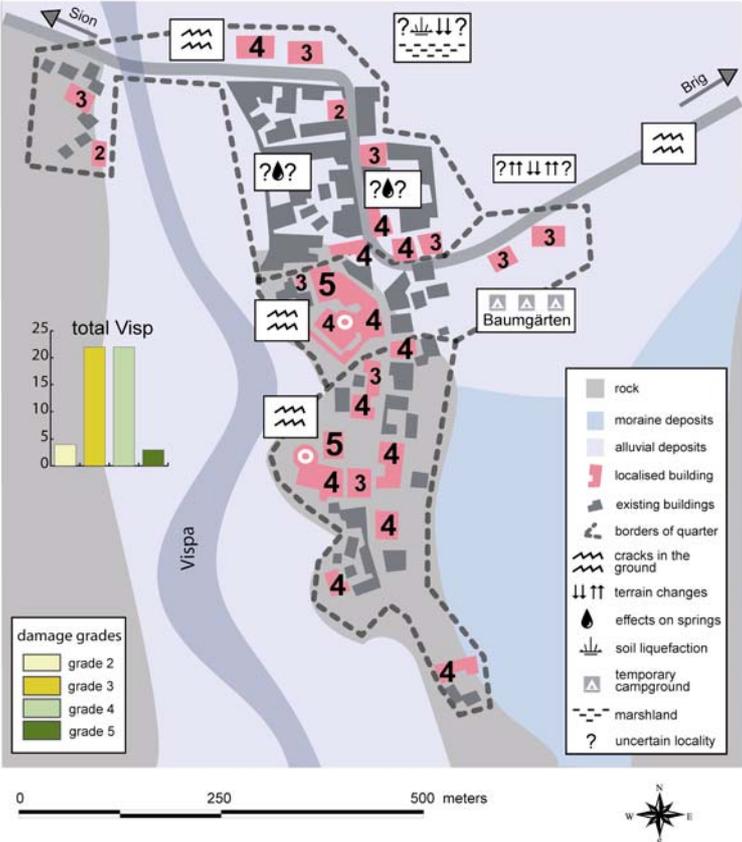


Figure 3: Damage and secondary effects observed in Visp during the 1855 earthquake (modified from Fritsche et al., 2006a).

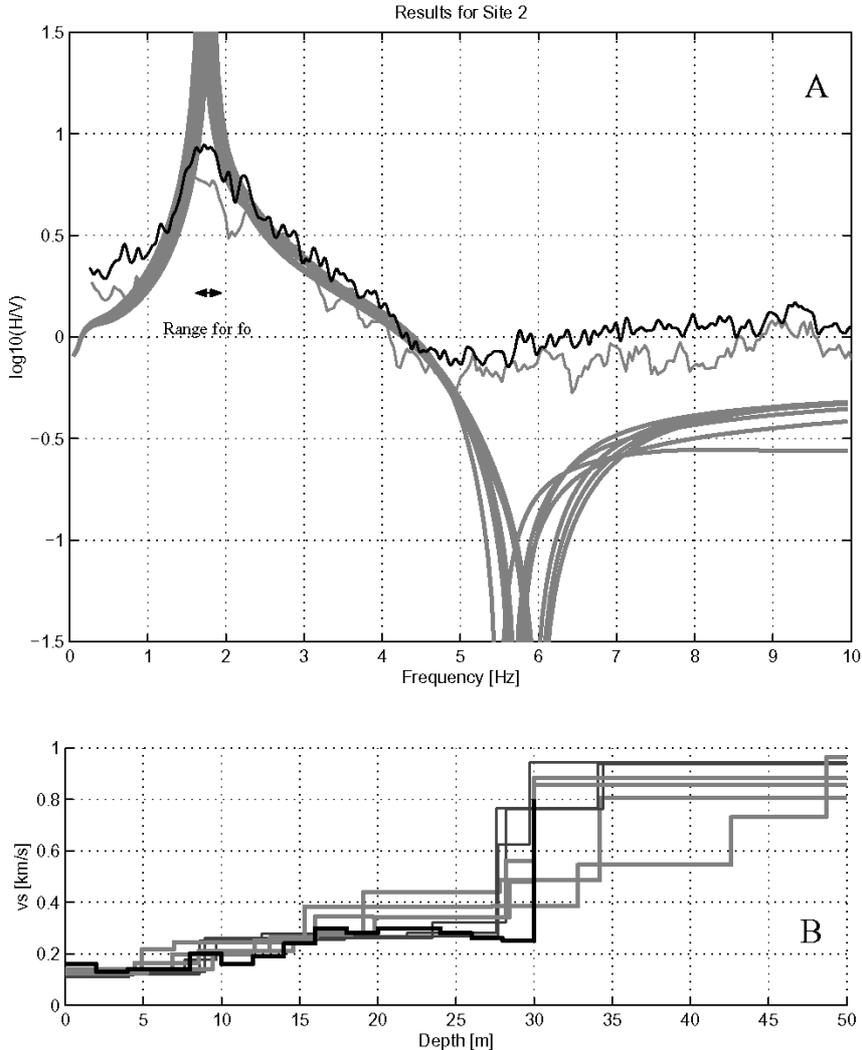
2. FUNDAMENTAL FREQUENCIES OF RESONANCE AND H/V SPECTRAL RATIOS

The fundamental frequency of resonance  $f_0$  can be measured with micro-tremors. These are ambient ground vibrations excited by natural or artificial disturbances such as wind, sea waves, traffic, and industry. They can be recorded using high sensitivity seismometers. The H/V method proposed by Nogoshi and Igarashi (1971) and Nakamura (1989) has proven to be convenient in estimating the fundamental frequency of soft deposits (e.g. Field and Jacob 1993; Lachet and Bard 1994; Lermo and Chavez-Garcia 1994). The spectral ratio between the recordings on the horizontal and vertical components exhibits a large peak at the fundamental frequency of resonance  $f_0$ , as long as the S-wave velocity contrast between the sediments and the bedrock is large. The results are clear and simple in case of horizontally layered structures with large impedance contrasts. This method was validated during the European project SESAME project (<http://sesame-fp5.obs.ujf-grenoble.fr>). However the seismic noise wavefield is complex. When interpreting the H/V ratio, one has to consider possible contributions to it from both surface and body waves, including higher modes of surface waves. Figure 4 shows a measured H/V spectral ratio at a site with a strong velocity contrast between sediment and bedrock.

In cases where the thickness of the soft sediments is known from borehole information or seismic measurements, H/V spectral ratios can be used to estimate average shear wave velocity with the simple formula:  $v_s = f_0 * 4h$ , where  $h$  is the thickness of the soft sediments. By knowing the fundamental frequency of resonance, we also qualitatively know the expected amplification as a function of frequency: The expected amplification is in general large at the fundamental frequency of resonance and significant for the frequency range above, but absent in the frequency range below about  $f_0/2$ .

The amplitude of the H/V spectral ratio at the fundamental frequency  $f_0$  indicates the S-wave velocity contrast between bedrock and sediments, and provides information on the severity of possible resonance effects during earthquakes. The higher the amplitudes, the larger the velocity contrast will be. However, the amplitude of the H/V ratio depends not only on the velocity contrast but also on the source-depth and source-distance distributions. Therefore, amplitudes of the H/V ratio only qualitatively indicate possible resonance effects.

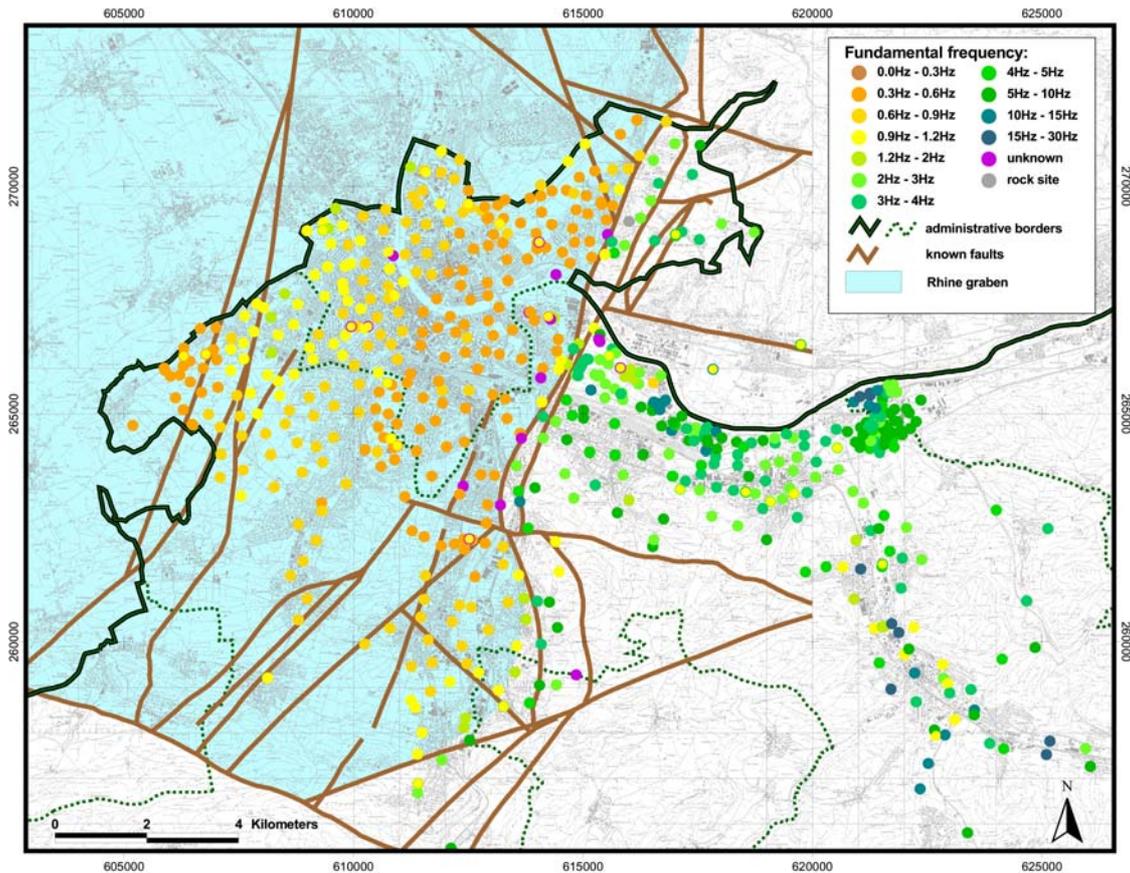
Due to often strongly excited fundamental mode Rayleigh waves in the ambient vibration wavefields, the average H/V spectral ratios can be assumed to measure the ellipticity of the fundamental mode Rayleigh wave. The ‘ellipticity’ at each frequency is defined as the ratio between the horizontal and vertical 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), Satoh et al. (2001) and Parolai et al. (2006) applied this idea to deep sedimentary basins. Fäh et al. (2001, 2003, 2006) applied it to shallow sites, proposing also a method based on frequency-time analysis that helps retrieve the ellipticity of fundamental mode Rayleigh waves from H/V spectral ratios. The use of ellipticity, however, only applies to sites with strong S-wave velocity contrast between sediments and bedrock, visible in a strong peak of the H/V spectral ratio. An example of this method is shown in Figure 4. An inversion using a single H/V spectral ratio needs constraints for the thickness of the sediments.



**Figure 4: Top: Comparison between H/V ratios in  $\log_{10}$  scale of observed noise at a soft-sediments site (thin black line: classical method; thin grey line: method based on frequency-time analysis) and the ellipticity of the fundamental-mode Rayleigh waves for different inverted structures (thick grey curves). Bottom: Structural models obtained from the different inversions of the observed H/V ratios (grey lines) compared to the obtained structure from seismic borehole measurements (black line) (modified from Fäh et al., 2003).**

A large number of  $f_0$ -measurements can result in a fundamental frequency map as shown in Figure 5 for the Basel area. The fundamental frequency follows the main geologic features. The deep structure of the Rhinegraben is clearly separated from the Tabular Jura by the observed low fundamental frequencies of resonance. Mapping the amplitude of the H/V spectral ratios indicates the velocity contrast between sediments and bedrock (Figure 6). Within the Rhinegraben different areas can be distinguished by different velocity contrasts between sediments and bedrock. The areas with thick Meletta layers, a soft argillaceous material, show large amplitudes of the H/V ratios and clearly separate from the Tüllinger layers. The latter consist of calcareous to argillaceous marls with layers of freshwater carbonates. For areas outside the Rhinegraben, the amplitude of the H/V ratio maps the S-wave velocity of the bedrock mostly.

H/V spectral ratios can be considered a fingerprint of the local structure. By comparing measurements within an area, similar H/V curves are observed for similar local structures and therefore show similar amplification effects during earthquakes. Such comparison can therefore be used to define a zone.

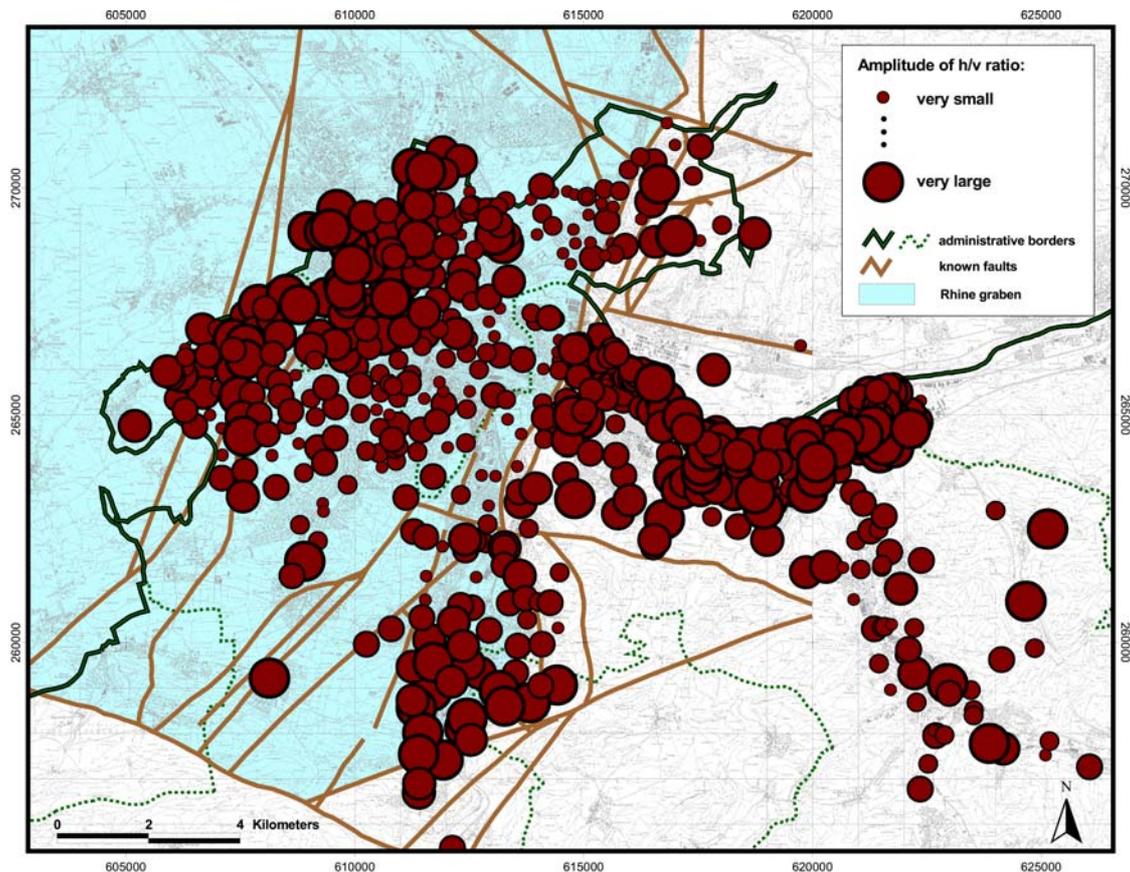


**Figure 5: Measurements of the fundamental frequency  $f_0$  of resonance in the Basel, Switzerland area. The main faults are drawn with brown lines. The Rhinegraben structure (colored in light blue) is visible through the low values of  $f_0$ . The Tabular Jura structure is covered with thin layers of soft sediments and the observed values of  $f_0$  are mainly above 2Hz.**

### 3. ARRAY METHODS

Dense array measurements of ambient vibrations tend to measure phase velocities of surface waves through analysis of spatial correlation (Aki, 1957) or high-resolution, beam-forming analysis (Capon, 1969). Then P- and S-wave velocity profiles can be derived by inversion. Several studies (e.g. Horike, 1985; Malagnini et al, 1993; among many authors) have illustrated how such array measurements can obtain velocity profiles. During the European project SESAME (e.g. Bard et al., 2004), the team developed a tool for using and comparing different array techniques (Ohrnberger et al., 2004; Wathelet, 2005). They also developed strategies for successful measurement.

The array method we use is based on the high-resolution frequency wave number estimator proposed by Capon (1969) and developed for vertical recordings of ambient vibrations by Kind et al. (2005). Recently, this method has been extended for analysis of horizontal components (Fäh et al., 2006b). Ambient vibrations recorded within the array are therefore analyzed for all three components of motion. The dispersion curves of the fundamental mode and higher mode Rayleigh waves are extracted from the vertical component and the radial component of the propagating waves. Love waves are extracted from the transverse component of the propagating waves. Using all components allows us to identify the different modes, especially where so-called “mode-jumping” occurs. As a prerequisite for successful measurement, careful placement of the instruments is required. In general different apertures are selected for the measurements. Small array apertures are used to resolve the shallow part of the structure. By increasing the aperture, deeper and deeper structures can be investigated, and a dispersion curve can be developed over a wide range of frequencies.



**Figure 6: The same area as shown in Figure 5, but mapping the amplitude of the H/V spectral ratio to indicate the velocity contrast between sediments and bedrock.**

Different array configurations were tested in the field and with synthetic signals. Numerous sites were investigated in the Basel and Valais areas to define the S-wave velocities of geological layers down to 150-250m. During the Interreg Project “Seismische Mikrozonierung am südlichen Oberrhein” (seismic microzonation of the southern upper Rhine) (2003-2006) array techniques were applied to 27 sites in the Basel area (Figure 7). An example of measurements at the site of a strong-motion station (station SMZW) is given in Figures 8 and 9. Generally, array measurements allow resolution of the S-wave velocity structure down to the bedrock. But uncertainty increases with increasing depth. Determining the S-wave velocity of the bedrock would require arrays with a larger aperture. Within the Interreg project, a series of measurements were performed to compare ambient vibration techniques with active S-wave seismic methods and spectral analysis of surface waves (SASW). Such comparisons proved the array method very competitive for seismic investigation at the medium depth range of several tens to hundreds of meters (Havenith and Fäh, 2006, in preparation). At some sites, however, considerable differences were found between active seismic and passive array techniques. Possible reasons for this are the different frequency bands of the waves used or the presence of non-layered structures. In the latter case, array techniques cannot be applied over the entire frequency band of interest.

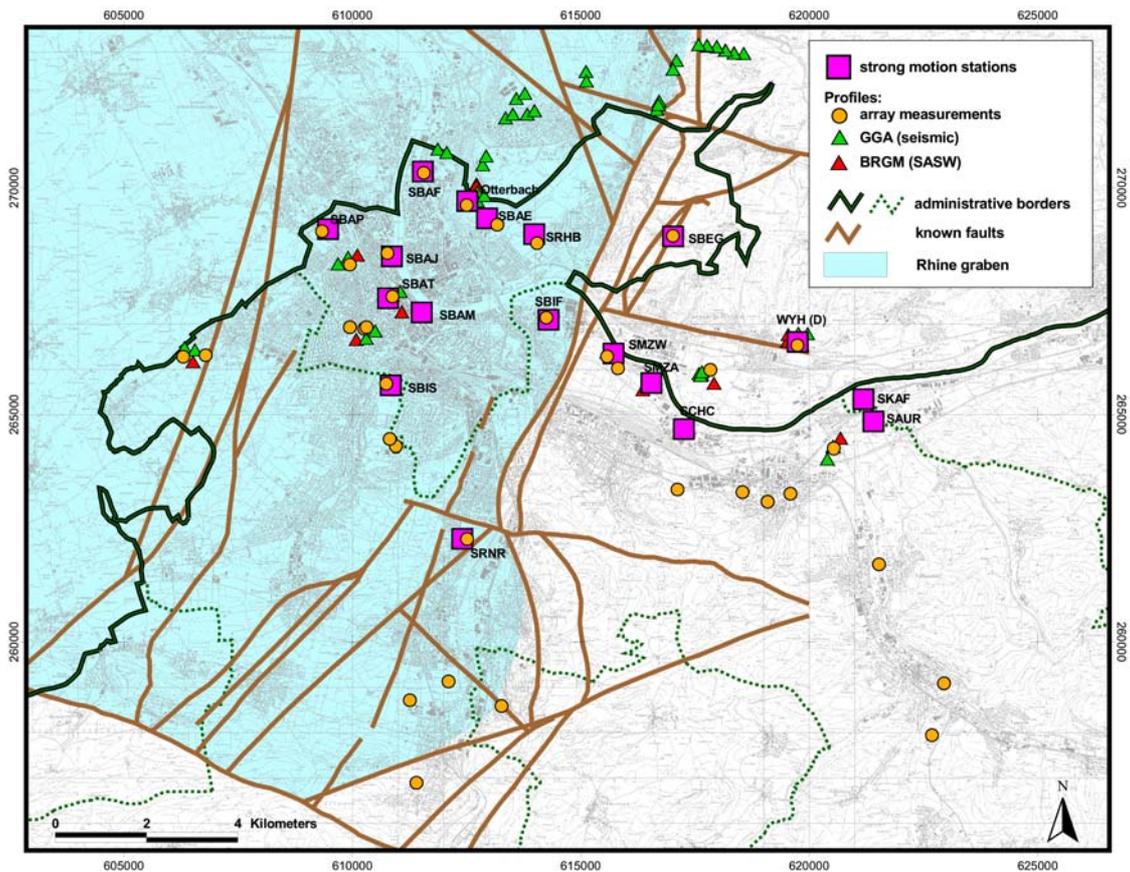


Figure 7: Measurement sites in the Basel area (Interreg Project “Seismische Mikrozonierung am südlichen Oberrhein”, 2003-2006) and locations of the strong motion stations. Different methods were applied: ambient vibration array measurements by SED (orange circles), seismic measurements performed by the *Geowissenschaftliche Gemeinschaftsaufgaben Hannover (GGA)* (green triangles), SASW measurements performed by the *Bureau de Recherche Geologique et Minière (BRGM)* (red triangles). The locations of two stations in the permanent strong motion network of the Swiss Seismological Service are given as red squares.

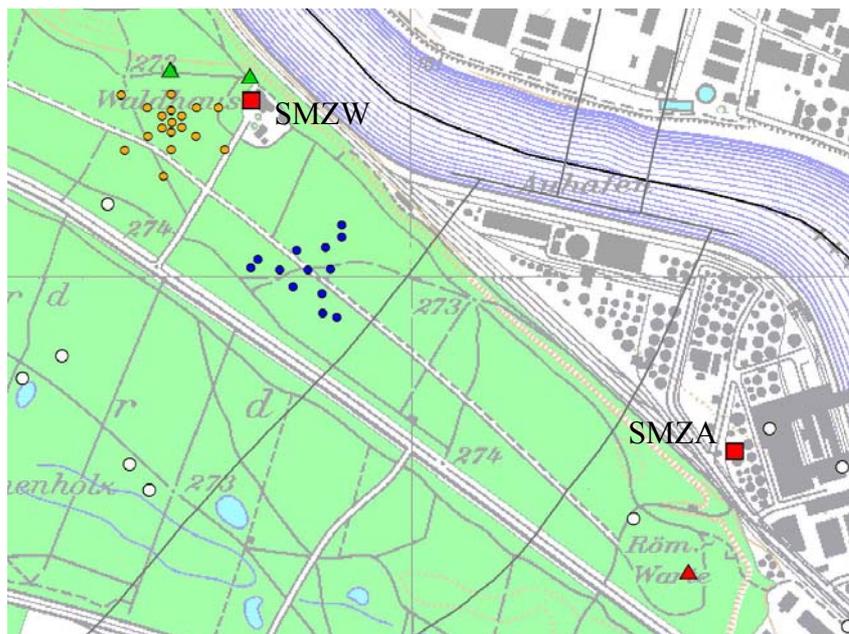
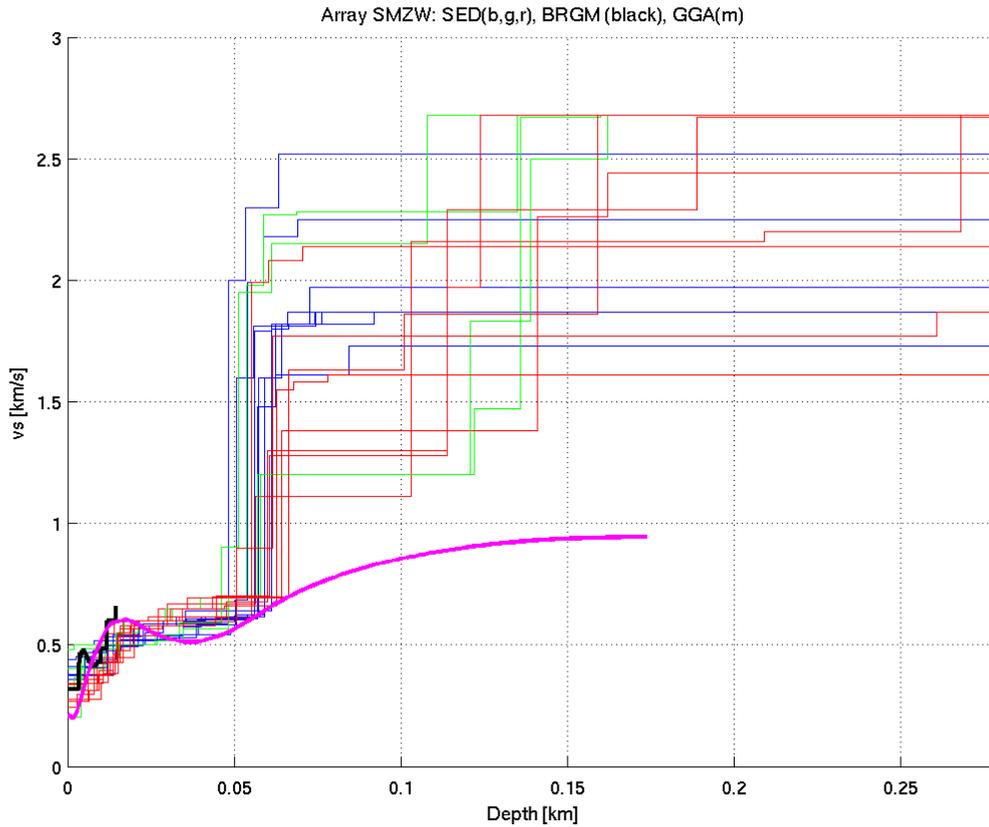


Figure 8: Example of two array configurations (blue, red) applied in the area of Basel. Boreholes are given as white circles, the other symbols are explained in Figure 7.

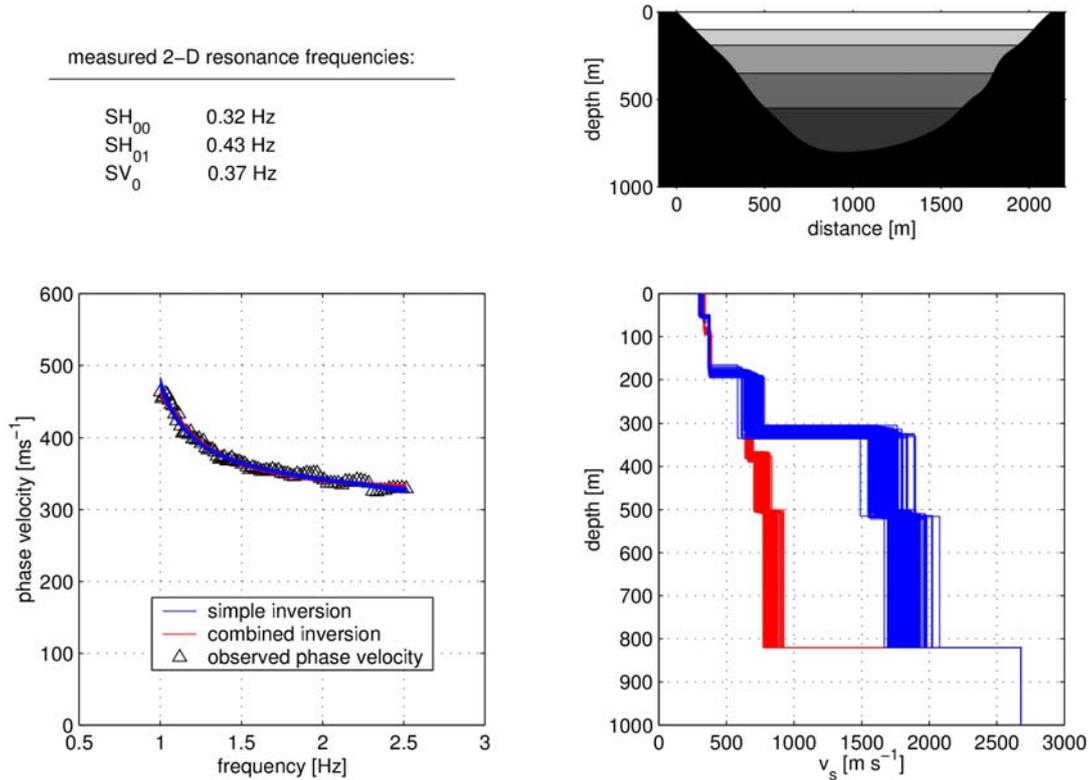


**Figure 9: Inverted S-wave velocity models from the measurements shown in Figure 8. The results from the array measurements (red, blue, green) are compared with those from the seismic (magenta) and the SASW (black) measurements.**

#### 4. AMBIENT VIBRATION MEASUREMENTS IN 2D STRUCTURES

In the Alpine area many cities are located in river valleys which can often be approximated by a 2D structure. In such locations 2D effects may contribute significantly to earthquake ground motion. Edge-generated surface waves dominate in shallow valleys, while 2D resonance patterns develop in deep basins. Estimating ground motion amplification with numerical simulations requires a realistic geophysical model of the structure. This needs field investigation techniques which can measure S-wave velocity as a function of depth in a 2D structure. In addition to active seismic techniques, cheap and efficient ambient-vibration methods can once again be applied. Array methods rely on two assumptions: that the observed noise wavefield consists mainly of horizontally propagating surface waves, and that the structure can be approximated by horizontal layers. At higher frequencies, propagation waves can be observed and analyzed with array methods. In 2D structures, however, the wavefield at low frequency consists of standing waves, given the 2D resonance. To identify the resonance frequencies, site-to-reference spectral ratios can be applied to the ambient vibration wavefield (Steimen et al., 2003; Roten et al, 2006). Combining this technique with an analysis of spectral amplitude patterns and phase behavior along the valley profile allows us to identify the fundamental and higher modes of SH and SV resonance.

Roten and Fäh (2006) propose a combined inversion of dispersion curves and 2D resonance frequencies. The dispersion curves are obtained with circular arrays that sample the upper part of the sediment-filled valleys. Different resonance frequencies define the deeper part of the structure. Figure 10 compares results of a simple inversion of the phase velocity curve with results of a combined inversion for one site in the Valais, Switzerland. We see that scatter in the models is significantly reduced and the combined inversion resolves the structure down to the sediment-bedrock interface.



**Figure 10: The results of inverting the measured phase velocity curve (blue) compared with those from a combined inversion (red) using measured resonance frequencies as well (modified from Roten and Fäh, 2006). The site is near Saillon in the Rhone Valley, Valais. The 2D section of the valley and measured resonance frequencies are shown above the figure.**

## 5. NUMERICAL PREDICTIONS

Once a structure is well established with different field measurements, we can apply numerical simulations of ground motion. We distinguish between different levels of sophistication in the methods. These include how we treat different complexities of geometry (1D, 2D, 3D, topography); soil behaviour (linear elastic, linear anelastic, equivalent linear, non-linear); the vertical incidence of waves, and inclusion of the source in modelling. Even when numerical methods are reliable, they require many input parameters. Modelling with a sophisticated method is recommended only when all input parameters can be defined with a limited uncertainty. The frequency band of interest in engineering seismology corresponds to about 0.5-10Hz, the range of the resonance frequencies of buildings and construction.

Different studies have been performed in Switzerland recently: for Basel (Fäh et al., 1997; Kind, 2002; Oprsal et al., 2005), Augusta Raurica, the site of an ancient Roman city (Fäh et al., 2006a), and the Valais (Roten et al., 2006; Havenith et al., 2006). Figure 11 compares numerical modelling for 2D structures (Kind, 2002) with 3D modelling (Oprsal et al, 2005), using a 3D model of the Basel area. Kind (2002) studied the 2D SH-wave propagation effects with a hybrid method combining modal summation and finite differences (Fäh et al., 1994). Kind performed a series of 2D computations for various point source mechanisms, depths, distances and positions. For the 2D structures and a 1D reference model of the Tabular Jura, computations allowed for the definition of amplification effects. Spectral amplification (for response spectra with 5% damping) was computed for six individual sections of surface receivers in the 3D model, totaling 84 scenarios. The city of Basel was subdivided into five zones representing the different range of the sediments' fundamental frequency of resonance (Figure 11 top left). Amplifications obtained for each zone were collected and analyzed. Amplification effects in the 3D model were studied by Oprsal et al. (2005) using the finite difference technique. The five spatial zones and the reference bedrock structure remained unchanged. Computations were performed for a large number of receivers at the surface of the 3-D model by using extended seismic sources to the west, south and east of the city. Comparison of the 2D and 3D models is shown in Figure 11.

### Comparison of amplifications:

enveloped maxima (—); enveloped averages (—)

2D computation - thin lines; 3D computation - thick lines

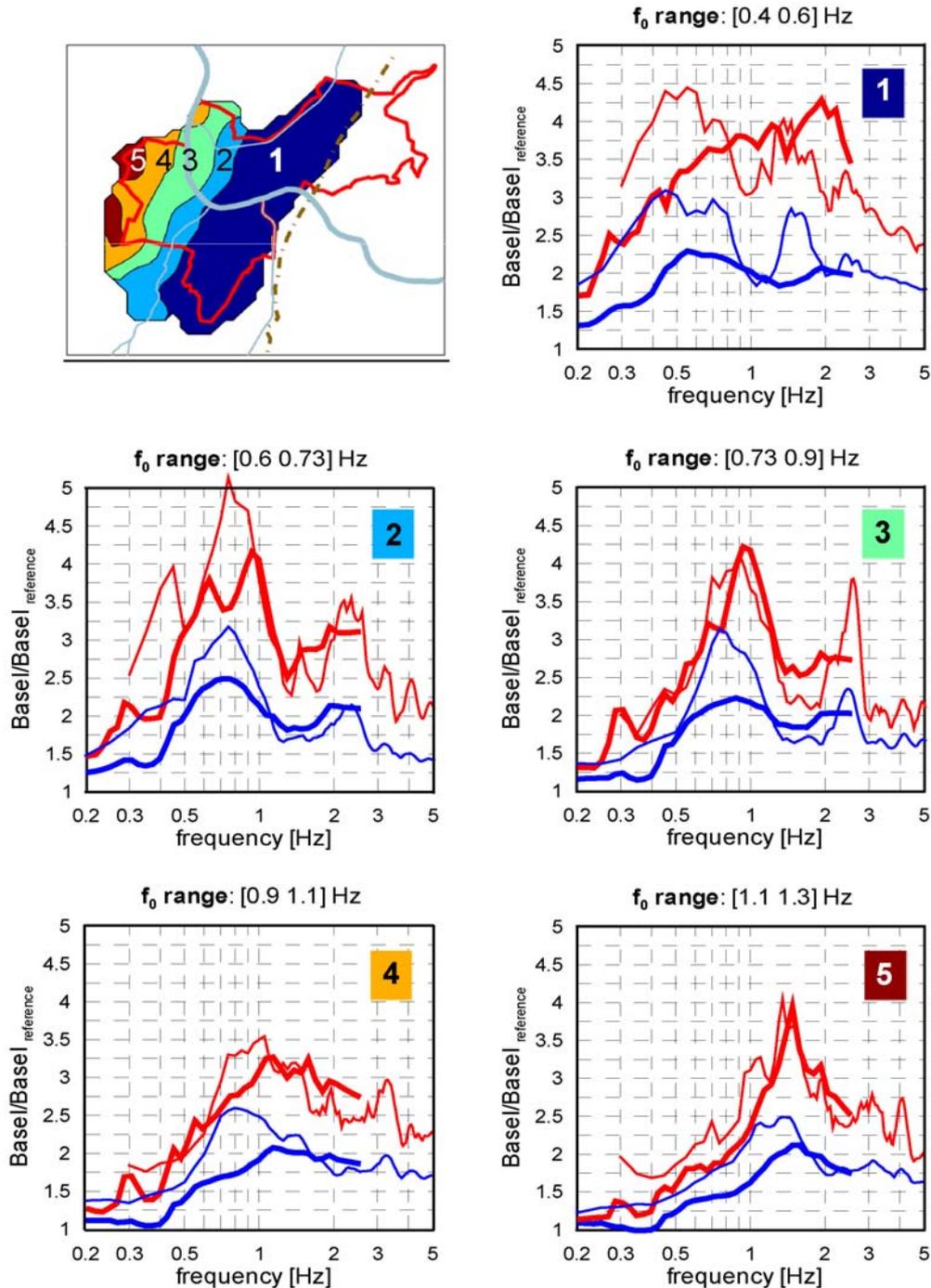
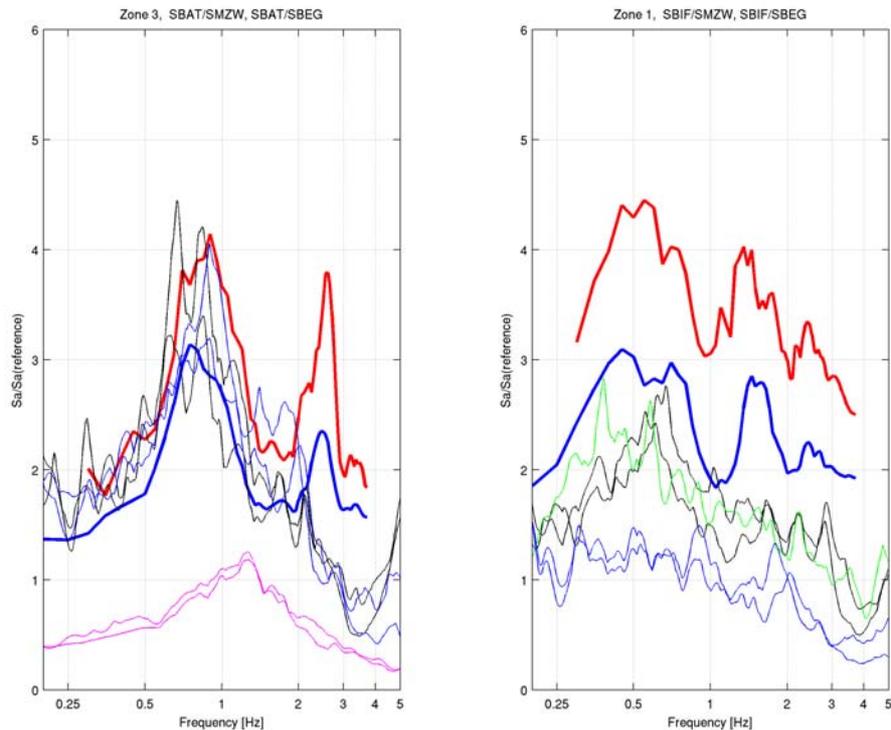


Figure 11: Spectral amplifications compared for response spectra with 5% damping in five zones in the city of Basel. Top left: The spatial extent of the zones is defined by the fundamental frequency of resonance shown in Figure 5. The thick lines in the amplification plots correspond to results from 3D modeling, using sources to the west, south and east of the city (Oprsal et al., 2005). The thin lines were obtained by 2D SH-wave propagation modeling for various cross sections and 84 earthquake scenarios (Kind, 2002). For each zone, the red lines show the overall maximum amplification from all scenarios. The blue lines denote the envelope of the average amplification curves for the different scenarios.

The largest differences between 2D and 3D modeling are obtained in zone 1. This zone is located in the Rhinegraben at the transition between Tabular Jura and Rhinegraben, where 2D and 3D effects are expected. The details of the structural model and modeling technique (3D wave propagation, relative location of the source) play an important role here. Comparing 3D and 2D modeling for zones 2-5 is similar. It suggests that for some applications it would be sufficient to apply 2D modeling and consider only SH wave propagation for quantifying amplification effects.

## 6. VALIDATION OF NUMERICAL RESULTS WITH RECORDINGS FROM LOCAL SEISMIC NETWORKS

Modelling should always be combined with observations of weak or strong motion recordings from earthquakes in the areas of interest. This requires dense seismic networks, which operate long enough to record a large number of events for statistical analysis. For areas of moderate seismicity such as Basel, strong earthquakes are very rare. Mostly weak motion data are recorded. During the last three years some events triggered the strong motion stations in Basel (Figure 7) with sufficient energy at low frequencies below 1 Hz. Even if the ground motion level of the events is low ( $0.05\text{-}0.1\text{ m/s}^2$ ), the recorded signals are useful for checking results of numerical modeling. Close to Basel none of the strong motion stations is located on good quality bedrock. However, due to the difference in the fundamental frequency of resonance  $f_0$  of the sediments between the stations inside and outside the Rhinegraben, we can use the stations outside as reference sites for the low-frequency part of the wave field. We have selected two reference stations: SBEG ( $f_0$  is between 3.8 and 4.2 Hz) and SMZW ( $f_0$  between 2.6 and 3.2 Hz). Figure 12 below shows the mean amplification of the horizontal components for two sites in the Rhinegraben: station SBIF in zone 1 and station SBAT in zone 3.



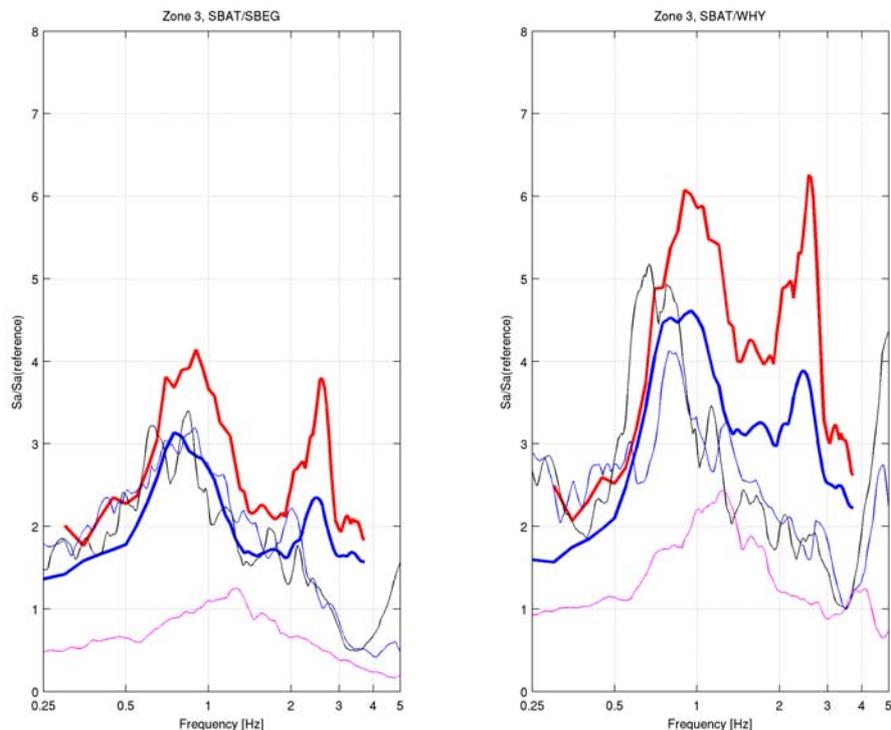
**Figure 12: Mean spectral ratios for the horizontal components between acceleration response spectra obtained for signals recorded at stations SBAT and SBIF within the Rhinegraben and the sites SBEG and SMZW located outside, obtained from recorded ground motion in Basel during earthquakes since 2003 (thin curves). The locations of the stations are shown in Figure 7. Curves for the horizontal components of motion are compared to the numerical prediction (thick blue line: mean amplification from 2D modeling; thick red line: maximum amplification from 2D modeling).**

The results in Figure 12 show good agreement between numerical predictions and observations. This is valid for all recording stations in Basel. Stations like SBAT reach the highest amplification levels, while SBIF reaches only the average. As we learned from modeling, site response depends on the source characteristics and location, and observed events are only some of many possible realizations.

## 7. SITE CHARACTERIZATION OF THE SEISMIC STATIONS AND ATTENUATION LAWS

Uncertainty in ground motion attenuation laws has been identified in Switzerland during the PEGASOS project (e.g. Scherbaum et al., 2005) as well as the Swiss Hazard project (Bay et al., 2003; 2005; Giardini et al., 2004; Wiemer et al., 2006) as the primary source of uncertainties in hazard assessment. This, however, is not simply a Swiss problem: the same is true to some extent worldwide. A large part of the variability in ground motion is due to the complexity in earthquake source, path and site conditions, all of which are known imperfectly. To reduce this uncertainty, ground motion records and derived attenuation models should be classified according to subsurface structure. However, information on site conditions is lacking for almost all seismological stations on rock sites and soft sediments in Switzerland. Only a few sites have been investigated so far (see Figures 7 for examples of investigations at a strong motion stations in the Basel area). We plan to perform measurements at all Swiss seismic stations within the next 10 years, an ambitious undertaking due to the high cost.

One of our main targets is to define the “reference rock” in seismic hazard assessment. Well-defined typical soil classes are needed for regional ground motion attenuation models and microzonation studies. The problem we are facing today is illustrated in Figure 13. The amplification at stations SBAT is shown using station SBEG and the more distant station WHY as reference. Station WHY is part of the network of the Landeserdbbendienst Baden-Württemberg. This strong motion station is placed in an ancient quarry on high-quality bedrock. At this site  $v_s$ -measurements have been performed and high  $v_s$ -velocities were identified at shallow depth. Amplification observed at station SBAT is about 1.5x higher when using station WHY as reference. This variation can be explained by the velocity structures of the different stations and illustrates the need for a well-defined reference structure.



**Figure 13: The same as in Figure 12 for station SBAT, using recordings from station SBEG (left) and from station WHY (right) as reference.**

In regions of moderate seismicity like Switzerland, however, the problem of attenuation laws is exaggerated by the fact that magnitude 5 or larger events are rare. Thus, few data are available that constrain the scaling of ground motions from the more frequent small events to the infrequent large ones (Bay et al., 2003; 2005). To improve attenuation relations, ground motion recordings from other areas should be included in the calibration dataset, after the site of each recording station has been carefully investigated.

## 8. CONCLUDING REMARKS

Combining cheap seismic field investigation tools, modern numerical methods which simulate earthquake source and path effects, and observations of seismic ground motion allows us to reliably model site-specific earthquake ground motion. The findings are important as basic inputs for future building codes. Site characterization of the seismic stations in a network will also enable site-specific attenuation relations. As a result, we may reduce uncertainties in assessing probabilistic seismic hazard and in defining response spectra in microzonation studies.

Earthquakes are inherently complex phenomena, beginning with the physics of rupture nucleation, propagation and arrest and the excitation of seismic waves propagating through geologically heterogeneous structures. They are the cause of several coupled primary, secondary and tertiary hazardous processes. Earthquake strong ground motion acts on buildings and infrastructure and may have considerable effects on the environment. In the Alps, earthquakes are known to have caused widespread liquefaction, subsidence and lateral spreading in fluvial and lacustrine deposits as well as landslide failure and mobilization, the formation of landslide dams and outburst floods. Considerable effort and resources have been devoted to understanding of single hazards in the past and they were studied more or less independently. Future developments will address the compound or coupled hazard of primary, secondary and tertiary hazards and will work on the physical interaction between the individual natural hazards related to strong earthquakes. Realistic consideration and combination of the different earthquake induced effects will significantly improve potential damage evaluation, and will help us to mitigate earthquake related impacts. In particular, it will provide answers to a crucial question in earthquake risk mitigation: what are the direct and indirect effects of a large earthquake?

## 9. ACKNOWLEDGMENTS

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