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ASSESSMENT OF THE COMPLEX SEISMIC RESPONSE OF GEOLOGICAL STRUCTURES

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ABSTRACT

Understanding the influence of local geology on recorded seismic ground motion is a key issue for reliable site-specific seismic hazard assessment. This is true for any near-surface structure, from sedimentary basins to outcropping hard rock. A wide range of passive and active seismic single-station and array methods exist, that allow us to estimate the S-wave velocity profile and its lateral variability around seismic stations, and to assess the complexity of the local seismic response at the site. For instance, polarization features of the ambient vibration wavefield help to identify possible 2D/3D resonances, and spectral modeling of the earthquake recordings in seismic networks can confirm the occurrence of such resonances. Spectral modeling also allows the estimation of the influence of edge generated surface waves through comparison with numerical simulation of the site response. Finally, the possibility of non-linear soil behavior can be assessed using CPT measurements combined with non-linear site response analysis at particular sites.

Using one or several passive seismic arrays, we are able to measure Love and Rayleigh wave dispersion curves using different methods, e.g. SPAC, 3-component HRFK, and WaveDec implementing a maximum likelihood approach. The Rayleigh wave ellipticity and particle motion (prograde or retrograde) is an important parameter to constrain the velocity contrast between sediments and bedrock. 2D resonance effects in narrow Alpine valleys can be detected by identifying constant polarization features in all single-station H/V measurements inside the valley. Applying frequency-domain decomposition methods on ambient vibration recordings using linear arrays along the valley cross-sections, we can further separate different 2D resonance frequencies and their corresponding modal shapes.

The same methods can be applied to sedimentary slopes and to analyze weathered and competent rock. Particular features can be observed on fractured rock instabilities. Recorded ground motions (earthquakes or ambient vibrations) are directional in the unstable part of the rock slope, and significantly amplified with respect to the stable areas. These characteristics allow mapping stable and unstable portions of the rock mass, with predominant directions of ground motion typically matching past or on-going displacement directions.

Keywords: strong motion, site effect, earthquake engineering, site characterization

INTRODUCTION

Site response related to near-surface geological structures is a key issue in seismology due to its importance in seismic hazard assessment, whether for improving regional assessments of wave propagation effects, or for site-specific hazard analyses. Site-specific characterization is typically applied in case of unconsolidated soil deposits overlying bedrock (e.g., Bard et al., 2010), but is also required for weathered and competent rock sites. Using earthquake records, site response is generally determined by the spectral ratio method using a reference station on a nearby hard rock. As a high level of seismicity or an adequate reference site might not always be present, other methods based on the recordings of seismic noise or non-reference methods for earthquake recordings have been proposed. The use of ambient vibration measurements has become increasingly attractive in a broad range of seismological disciplines at different scales, because of relatively simple and efficient data acquisition. In this field of research, the team at the Swiss Seismological Service (SED) developed a number of ambient vibration single-station and array-processing methods (Burjánek et al., 2010a; Ermert et al., 2014; Fäh et al., 2001; Kind et al., 2005; Maranò et al., 2012; Poggi and Fäh, 2010; Roten et al., 2006), and successfully applied them to site-specific seismic hazard studies (Burjánek et al., 2010b; Fäh et al., 2003; Havenith et al., 2007; Poggi et al., 2012; Roten et al., 2008). Other methods, such as RayDec (Hobiger et al., 2009), MUSIQUE (Hobiger et al., 2016) and SPAC (e.g. Aki, 1957) have been implemented at SED and are applied for site-characterization. All these methods have been successfully applied in particular for the characterization of seismic stations of the Swiss seismic network (Michel et al., 2014) and are discussed in this contribution. Ground motion models can be applied to model the Fourier amplitude spectra at a given rock reference at each station of the SED network within minutes after automatic earthquake detection and location (Edwards et al., 2013). From the difference between observed and modelled ground motion for a large number of events, site amplification functions and their variability can be derived and related to the properties of the site. Such observations allow classifying station sites according to particular phenomena such as resonances or edge generated surface waves.

Several studies have also been conducted in the past decade regarding analysis of ambient vibration recordings on unstable hill slopes. Havenith et al. (2002) estimated resonant frequencies of a rock slope instability using single-station H/V measurements. Danneels et al. (2008) used small-aperture seismic arrays to measure dispersion of surface waves and subsequently invert for the shear-wave velocity profile in the area of an active earth flow. Burjánek et al. (2010a) estimated amplification factors and identified a range of resonant frequencies for a large unstable rock slope by noise polarization analysis. Renalier et al. (2010) and Pilz et al. (2014) applied seismic noise tomography methods to resolve the shear-wave velocity structure of a landslide. Such a variety of studies reflects the different origins of ambient vibrations in unstable slopes, and consequently the variety of related subsurface structures.

SINGLE STATION AND ARRAY METHODS

All new installations of SED´s permanent strong-motion stations are followed by measurements to characterize the properties of the subsoil. Different methods are employed, depending on the site characteristics (Michel et al., 2014). Passive measurements of seismic noise are always performed. At mostly stiff sites, the near surface is characterized by active seismic experiments. At sites with potential liquefaction in the case of strong ground motion, CPT measurements are performed.

For the passive array measurements, one or more arrays of sizes adapted to the expected ground properties are deployed and record ambient vibrations for about 2 hours. The arrays usually consist of 10 to 16 sensors installed in a configuration with a suitable array response over the frequency range of interest. The locations of the single sensors are precisely measured by differential GPS. Recently, a method was developed to optimize array configuration for a particular site given a specific number of sensors (Maranò et al, 2014). Data are analyzed with different methods to retrieve the surface-waves properties and the resulting curves are finally inverted for obtaining shear-wave velocity profiles.

The first group of processing methods analyzes the data of the different sensors independently. The first of these methods is the classical H/V ratio (e.g. Nakamura, 1989). It can provide a good overview of the homogeneity of the sites at the different array sensors. However, it is only a proxy for the Rayleigh wave ellipticity due to contamination by different wave-types. More advanced single-station methods are preferred for this purpose. The HVTFA method (Fäh et al., 2009) limits the H/V calculation to the most energetic wave arrivals, using the vertical component as a trigger for Rayleigh waves. Therefore, its results are closer to the real ellipticity curve. The RayDec method (Hobiger et al., 2009) applies the random decrement technique (Cole, 1973) to three-component data in order to suppress all other wave types and enhance Rayleigh waves, yielding the ellipticity curve.

A different one-sensor technique is the polarization analysis following Burjánek et al. (2010a). This technique analyses the main directions of the wave polarization at different frequencies. It can resolve principal directions of ground motion polarization for specific frequencies, e.g. because of eigen-vibrations. For a site inside a deep and narrow alpine valley, the polarization analysis will retrieve the wave polarization at the 2-dimensional resonance frequencies of the valley. In many cases the valley axis corresponds to the polarization axis of the wave-field, indicating the excitation of the SH eigen-vibrations.

The second group of applied methods are passive array processing techniques. The SPAC method (Aki, 1957) is applied to the vertical components of the signal to determine the dispersion curve of Rayleigh waves. As it is unclear how the presence of several wave modes influences the SPAC curves, the usage is limited in such cases. An advanced method used is the 3-component high-resolution frequency-wavenumber (3-component HRFK) technique proposed by Fäh et al. (2008). In contrast to the original HRFK (Capon, 1969), which analyzes the data of a single component recording, this technique uses the recordings of all three components simultaneously. The northern and eastern components are rotated for each possible azimuth to form the radial and transverse components. The analysis of the transverse components then yields the Love wave dispersion curve. The vertical and radial components yield the Rayleigh wave dispersion and ellipticity curves (Poggi and Fäh, 2010). This method also showed good performance for large structures such as the Moesian platform in Bucharest area (Manea et al., 2016). Another 3-component array technique is the WaveDec technique (Maranò et al., 2012). This technique is based on maximum likelihood estimation of the parameters of several seismic surface waves. The simultaneous presence of multiple Rayleigh and Love waves is accounted for. The seismic wavefield is decomposed and wave parameters are iteratively re-estimated. It yields the dispersion curves for Rayleigh and Love waves, as well as the ellipticity angle for the Rayleigh waves. The ellipticity angle ranges between -90 and +90°. Negative values correspond to retrograde particle motion, positive ones to prograde particle motion. The classical ellipticity can then be obtained as the tangent of this angle. The usage of the ellipticity angle has several advantages compared with the classical ellipticity value as shown in the next section. Another advantage of the WaveDec method is that it also allows us to determine the parameters of several wave modes at the same time and therefore leads to a better separation of the different modes.

By combining the results of the different techniques, we define final dispersion and ellipticity curves for the site and invert them simultaneously for the shear-wave velocity profile below the site using the dinver code of the geopsy package, which implements the modified neighborhood algorithm (Wathelet et al., 2004). The parametrization of this non-linear inversion problem determines the quality of the final results that should reflect the uncertainties. For that purpose, a set of realistic profiles are delivered instead of a single one. The results of the site characterization are finally verified by comparing the theoretical SH transfer function with the empirical amplification of the seismic station, as determined from the recordings of numerous earthquakes (Edwards et al., 2013). This comparison may yield new hypotheses for the inversion or show the need for additional studies to assess non-1D effects.

RAYLEIGH WAVE ELLIPTICITY

Maranò et al. (2016a) focus their attention on the retrieval of Rayleigh wave ellipticity using the Maximum Likelihood method (i.e., WaveDec, Maranò et al., 2012), which has been applied to a number of sites in Switzerland. The sites examined are chosen to reflect a wide range of soil conditions that are of interest in local seismic hazard assessment. Fundamental modes and higher modes are retrieved. The sense of rotation of the particle motion (prograde vs. retrograde) is also estimated. Singularities of the ellipticity, corresponding to a change of the sense of rotation from prograde to retrograde (or vice versa), are detected with great accuracy (Figure 1).

Knowledge of Rayleigh wave ellipticity, including the sense of rotation, is useful in several ways. The ellipticity angle allows us to pinpoint accurately the frequency of singularities (i.e., peaks and zeros of the H/V representation of the ellipticity). Information about the prograde and retrograde particle motion can be valuable in mode separation and identification. Even though this feature is not yet implemented in the inversion procedure, the use of the ellipticity angle is an important additional observable with the potential to constrain the structural model in future inversions.

Figure 1 depicts the Rayleigh-wave ellipticity angle curve estimated at two different sites. The ellipticity angle curve at site SBAS reveals the two strong velocity contrasts at the site. In fact, Rayleigh wave particle motion is horizontally polarized at 2 Hz and 3.8 Hz. The ellipticity angle curve of SDAK shows a common pattern for a single strong velocity contrast at depth.

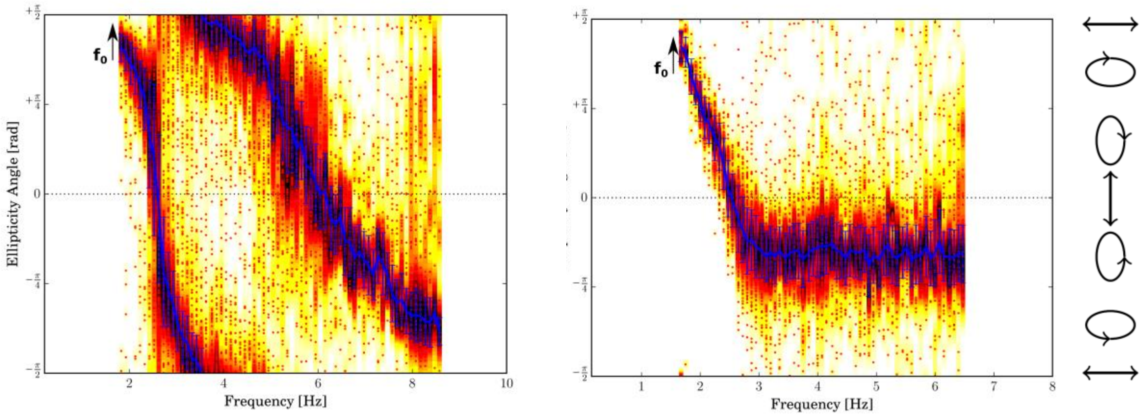

Figure 1. Rayleigh wave ellipticity curve retrieved at the sites of Baar, SBAS (left) with the fundamental frequency of resonance at 2 Hz, and the site of Davos, SDAK (right) with the fundamental frequency of resonance at 1.8 Hz. A positive ellipticity angle is obtained for prograde particle movement and negative angle for retrograde movement (from Maranò et al., 2016a).

COMBINATION OF ACTIVE AND PASSIVE METHODS

Applications analyzing Rayleigh waves include active and passive seismic surveys. In active surveys, there is a controlled source of seismic energy and the sensors are typically placed near the source. In passive surveys, there is not a controlled source, rather, seismic waves from ambient vibrations are analyzed and the sources are assumed to be far outside the array. With the goal of modeling the wavefield in the time domain, whenever the source is near the array of sensors or even within the array, it is necessary to model the wave propagation accounting for the circular wave front. In addition, it is also necessary to model the amplitude decay due to geometrical spreading. This is the case of active seismic surveys, in which sensors are located near the seismic source.

Maranò et al. (2016b) propose a Maximum Likelihood approach for the analysis of Rayleigh waves generated at a nearby source. Their statistical model accounts for the curvature of the wave front and amplitude decay due to geometrical spreading. Applications on real data of the retrieval of Rayleigh wave dispersion and ellipticity are shown in Figure 2. The method employs arrays with arbitrary geometry and can be combined with a passive survey on the same array configuration. As long as the structure can be assumed as 1D, the properties of Rayleigh waves from both types of surveys can be retrieved and show an excellent agreement. By combining active and passive surveys, it is possible to enlarge the analyzable frequency range and therefore the investigated depths in order to better constrain the inversion into shear-wave velocity profiles. Combining active and passive surveys by employing the same array of sensors simplifies the required logistics.

Figure 2 depicts Rayleigh wave dispersion in wavenumbers and ellipticity angle retrieved at the site of Zurich Airport (SKLW). The fundamental mode of the Rayleigh wave (R0) is identified both in the passive and the active surveys. There is a perfect agreement between the results obtained in the passive and active surveys.

NOISE CORRELATION

Array methods described in the previous sections retrieve surface-wave properties and are inverted into the S-wave velocity structure, albeit under the assumption that the underlying medium is not varying laterally. The method described in the following overcomes this limitation. Since the beginning of this century, seismic interferometry has rapidly become popular in a variety of applications. One of the most intriguing applications of the method, shown both theoretically and experimentally, is that a random wave-field has correlations, which, on average, take the form of the

Green´s function of the media. Between pairs of receivers, the Green´s function can be extracted from cross-correlations of ambient vibrations recorded at both receivers, in turn allowing an estimate of the propagation delay between the stations. Such travel-time measurements of Rayleigh waves reconstructed from seismic noise have been used at lower frequencies to produce high-resolution images on continental and regional scales.

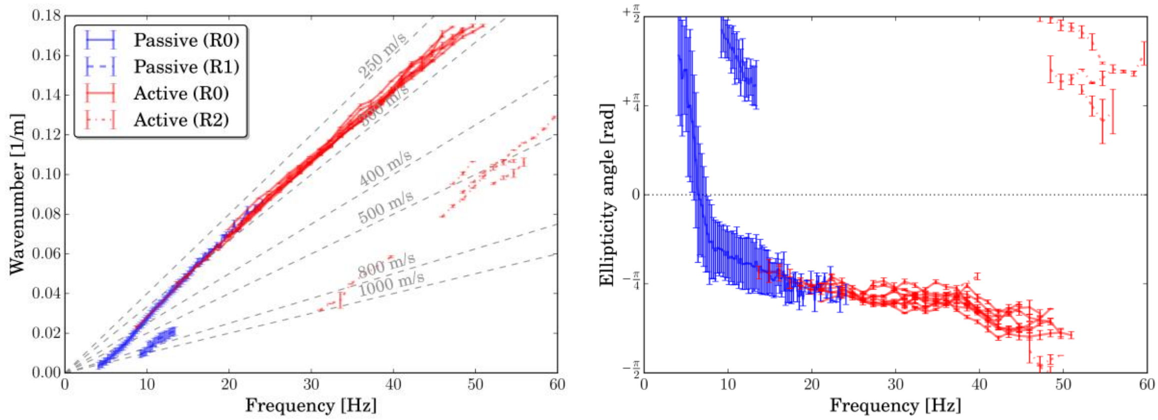

Figure 2. Results of joint active (red lines) and passive (blue lines) surveys at Zurich Airport (SKLW). The retrieved Rayleigh wavenumber curves are shown on the left panel, the retrieved Rayleigh wave ellipticity-angle curves in the right panel (from Marano et al, 2016b). Each red curve corresponds to the results for one shot.

However, only limited attention has been paid to this method for imaging shallow structures on much smaller scales. Although the use of high-frequency seismic noise requires a better understanding of the origin of seismic noise and of the spatial and temporal distribution of its sources, the method has also been shown to perform well for higher frequencies on local scales (Brenguier et al. 2007, Picozzi et al. 2009, Pilz et al. 2012, 2013, 2014). A limited number of stations and recording times of some hours allow detailed images of the local 3D subsoil structure to be obtained, even under pronounced topographic conditions (see Figure 3).
Since the method only uses the phase and not the amplitude information associated with the direct or scattered waves, the scattered part of the correlation functions is stable enough to provide robust velocity estimates. Moreover, since reliable velocity estimates for the frequency range investigated can be obtained rather fast due to increasing computing power, we expect that such methods can open the way to temporarily high-resolved imaging and monitoring of landslides and possibly also seismic faults.

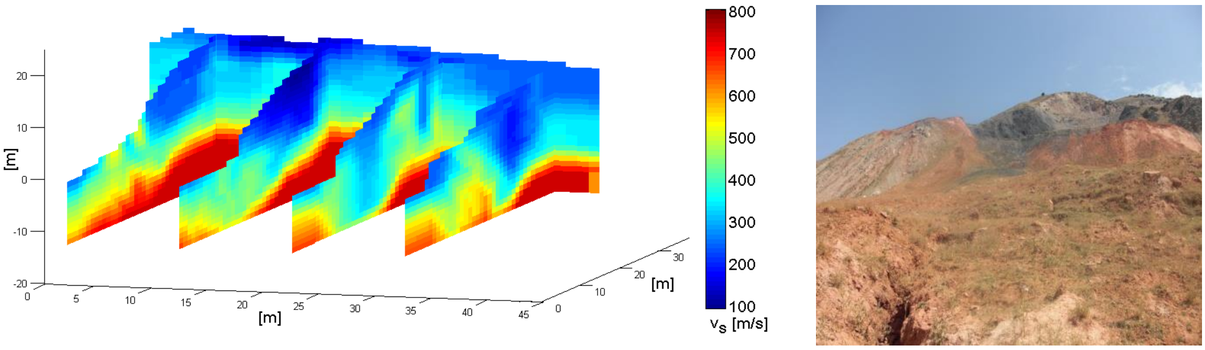

Figure 3. 3D S-wave velocity models of a hill slope in southern Kyrgyzstan (left). The photo of the hill slope (right) has been taken in the same direction of sight.

IDENTIFICATION OF 2D RESONANCES

Many of the techniques nowadays used in site response analysis have a focus on the definition of the one-dimensional amplification obtained by means of simplified assumptions on the site structure. Although this approach is applicable in many cases (e.g. Michel et al., 2014), several noteworthy exceptions exist. This is the case for sedimentary basins with a complex subsurface structure, such as irregular bedrock shape and topography or inhomogeneous seismic velocity distribution. In all these cases, ground motion is largely controlled by the specific geometrical features of the site and cannot be modeled without a sufficiently accurate knowledge of the whole site structure. However, standard seismic techniques might be too expensive to characterize the geology of large areas. As an alternative, site response can directly be evaluated in these environments using field observations, which allow the detection and qualification of 2D/3D effects caused by complex geometrical structures.
The development of 2D resonance patterns in narrow alpine sedimentary basins has been investigated through the implementation of new techniques for modal decomposition of the seismic wave-field and by means of numerical modeling (Ermert et al., 2014; Poggi et al., 2015). These studies have demonstrated the possibility of mapping the relative variation of ground motion along the transversal section of elongated axial-symmetric sedimentary basins (e.g. Rhone Valley, see Figure 4) by performing array analysis of synchronous ambient vibration recordings. This is essential for the evaluation of site response in such complex environments and particularly for the identification of areas of maximum (and minimum) expected amplification. These results, in combination with point estimates of the empirical amplification function, e.g. through spectral modeling (Edwards et al., 2013), give the possibility to have a full and cost-effective representation of the ground motion variability due to geometrical characteristics of the site.

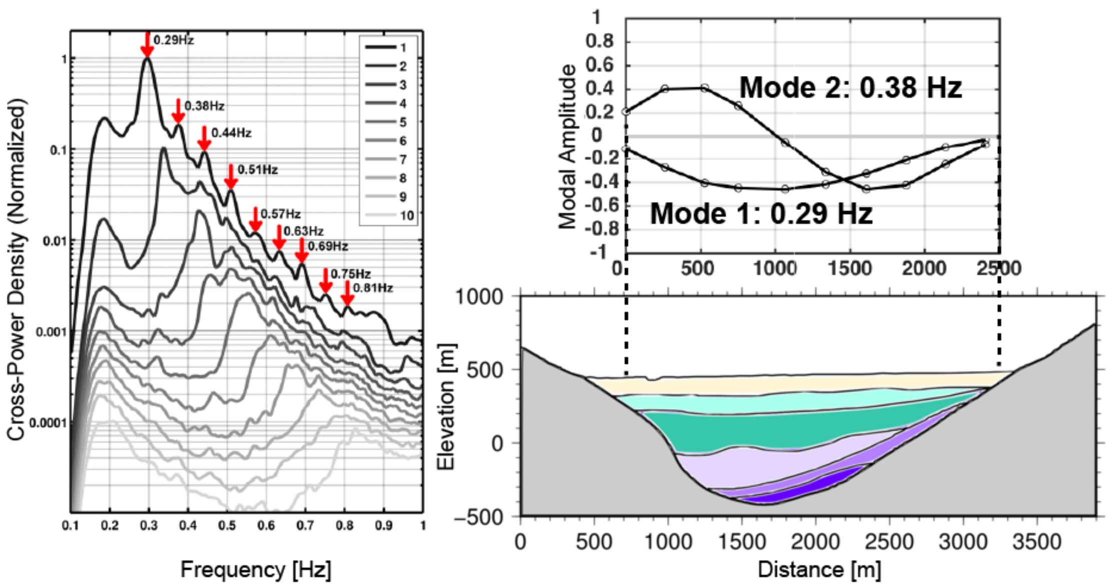

Figure 4. Results from modal decomposition of ambient vibration array recordings on a 2D Alpine valley (from Poggi et al., 2015, modified). On the left, eigenvalue spectrum showing the SH- fundamental frequency of resonance (0.29 Hz) and corresponding overtones. On the top right, the modal shapes at the fundamental frequency and the first overtone are shown along the valley cross-section (bottom right).

EMPIRICAL AMPLIFICATION

Following Edwards et al. (2013), the Fourier amplitude spectra (FAS) of recorded earthquakes at each station of the Swiss seismic network are modelled within minutes after automatic earthquake detection and location. All signals with sufficient signal-to-noise ratio are used to retrieve information about the source (moment magnitude M_W and stress parameter), attenuation and the average amplification, A_j, at

each site, j. The path (geometrical spreading and anelastic attenuation) is defined using a calibrated model for theoretical reference-rock condition. The residual misfit at each frequency of the modelling with respect to the observed FAS represent the frequency-dependent site amplification function at each site. The elastic Empirical Spectral Modelling (ESM) amplification function is retrieved by statistical analysis over all recorded events. The anelastic ESM amplification function, relative to the reference rock model $A_j \times a_j(f) \times e^{-\pi f \Delta\kappa_j}$ is also computed, with $\Delta\kappa_j$ defining the difference in attenuation between site j and the theoretical reference rock site. The reference of these amplification functions is the Swiss reference rock model defined in Poggi et al. (2011).
Edwards et al. (2013) and Michel et al. (2014) showed through comparison with other techniques that the ESM functions, even though sometimes based on few earthquakes only, are reliably depicting the amplification at each station of the Swiss network. Figure 5 shows the comparison of the ESM amplification functions ratio with the surface to borehole spectral ratio at site STIEG, located 15 km North of Zurich, where a surface accelerometer and a 123 m deep short-period borehole sensor are installed. More than 90 seismic events were recorded and automatically analysed since 2013. The ESM function matches the surface to borehole ratio and displays various peaks related to the site response of poorly consolidated siltstone at the surface. Amplification analysis through ESM overcomes the drawbacks of the Standard Spectral Ratio technique, which requires a reference station on rock and assumes that the effects of propagation between the stations are negligible.

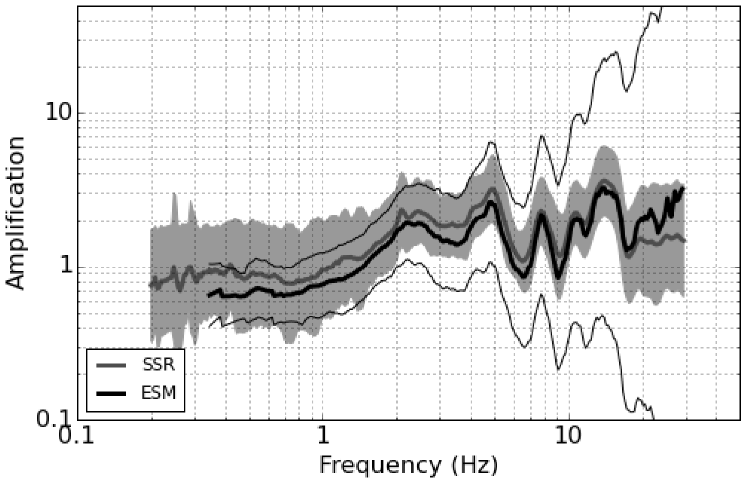

Figure 5. Comparison between ESM function ratios and surface to borehole spectral ratios (SSR) with their uncertainties at site STIEG.

The resulting amplification functions can be used to directly assess the local hazard. Results can be used in ShakeMaps (Cauzzi et al, 2015; Michel et al., 2016), to validate geophysical site characterization (Michel et al., 2014) or as an indicator for 2D or 3D site effects, especially for instable rock slopes (Burjanek et al., 2014), and sites characterized by the occurrence of edge-generated surface waves (Michel et al., 2014). The study of the near-surface anelastic attenuation $\Delta\kappa_j$ is a research topic by itself, and has proven particularly important to determine in the case of assessing seismic hazard for stiff structures, such as nuclear power stations (Edwards et al., 2015).

INSTABLE SLOPES

Especially in areas of large topographic relief, earthquakes trigger landslides and co-seismic slope failures. These effects significantly contribute to earthquake-induced damage. Recent observational studies performed on unstable rock slopes demonstrated a variety of site-effects associated with large local amplification levels (factors up to 70, see Kleinbrod et al., 2016). The shape of topography does not play a major role, while the internal structure of the instability is of primary importance (Burjanek et al., 2014). The nature of the observed site effects is highly complex, as a number of different mechanisms contribute. In general, the near-surface structure is strongly affected by slow gravitational deformations and other weathering factors including repeated earthquake shaking (Gischig et al., 2015). Consequently, shear-wave velocity can be reduced down to values typical for sediment sites

(<300 m/s). Moreover, rock could be intensely fractured, which further complicates the response (Moore et al., 2011). In particular, the presence of compliant macro-fractures in unstable areas results in directional amplification with respect to the stable areas (Figure 6). The predominant directions of ground motion match the past or on-going displacement directions (Burjanek et al., 2010a). Although the observed site effects are relevant to studies on slope's susceptibility to earthquake shaking, it helps understanding the slope's structure and stability as well. For example, directional and amplified ground motion can illuminate fractures and joints, which are not visible by geological observations due to soil cover and vegetation. Moreover, the volume and depth of the instability is related to the resonant frequencies.

We have developed and applied a number of methods for slope characterization based on the seismic response. It would be natural and straightforward to study seismic site response directly from the earthquake recordings, however, these are not always available (or just a limited number), so we rely mostly on the use of ambient vibrations. Conventional methods based on retrieval of surface-wave dispersion from the noise wave-field have been successfully applied at deep-seated instabilities characterized by isotropic rock damage (Burjanek et al., 2010b; Kleinbrod et al., 2016). On the other hand, surface waves do not propagate beneath the sites formed by discrete blocks and open fractures, where a normal-mode motion dominates the wave-field (Burjanek et al., 2012). Nevertheless, the deformation direction and resonant frequencies (see Figure 6) could be estimated by means of polarization analysis (Burjanek et al., 2010a).

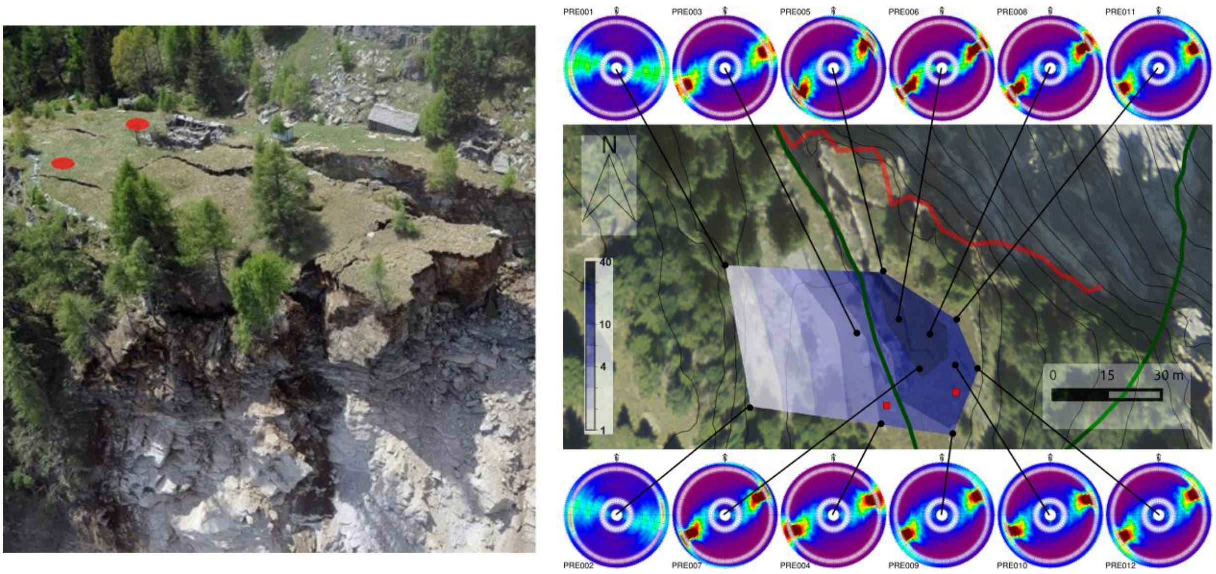

Figure 6. An array measurement at the unstable slope Alpe di Roscioro (Switzerland). Front view (view to the South-West, taken from helicopter) is presented at left, while the aerial view with the results at right. Ground vibrations are strongly amplified with respect to stable areas (amplification level at 3.2 Hz - bluish colormap) and highly directional in the instable areas at resonant frequencies (polar diagrams).

NON-LINEAR SOIL RESPONSE AND CPT MEASUREMENTS

The response of soft soils to seismic motion depends on the soil strength. While weak ground motions can result in amplification of seismic waves and longer shaking duration, high levels of strain can induce a decrease in shear stiffness and an increase in hysteretic damping. This non-linear behaviour generally translates into reduced high-frequency (f > 1Hz) amplification during strong motion (compared to weak ground motion) and a shift of the resonant frequency of the soil deposit to lower values. Such complexity has been confirmed by both laboratory experiments and field observations during large earthquakes (e.g., the 2000 Mw 7.3 Tottori earthquake and the 2011 Mw 9.1 Tohoku earthquake). However, it has been documented that soils do not reduce high-frequency ground motions in all cases: temporary drops in pore-water pressure may result in temporary recovery of shear

strength in the soil, therefore recovering its ability to transmit high-frequency waves even while experiencing large strains. High-frequency dilation pulses in sandy soils were observed in the strong motions of the 1987 Mw 6.8 Superstition Hills earthquake (Fig. 7), the 2011 Mw 9.1 Tohoku earthquake and the 2011 Mw 6.3 Christchurch earthquake, eventually exceeding 1g.
In order to predict the response of soils prone to pore water pressure build-up, phase transformations must be taken into account. Iai et al. (1995) showed that spiky waveforms recorded at site KP during the Kushiro-Oki earthquake could be reproduced using an advanced constitutive model capable of predicting pore-water pressure fluctuations. This soil model was implemented in the finite-difference code NOAH of Bonilla et al. (2005). Because such advanced constitutive model rely on a large number of parameters, its calibration represents a difficult task. Calibration by means of cyclic tri-axial tests performed in undrained conditions (e.g. Roten et al., 2009) can be problematic, as they may not reflect the *in-situ* behavior of the soil. Recently, Roten et al. (2013) and Roten et al. (2014) developed a method to calibrate the dilatancy parameters using vertical array records and successfully reproduced waveforms observed at the surface for different regions and earthquakes. The dilatancy parameters are found by minimizing the misfit between the observed and simulated surface acceleration. The computation of the surface acceleration from the borehole signal represents the forward problem, which is solved by NOAH. The parameter space is sampled using a neighborhood algorithm.

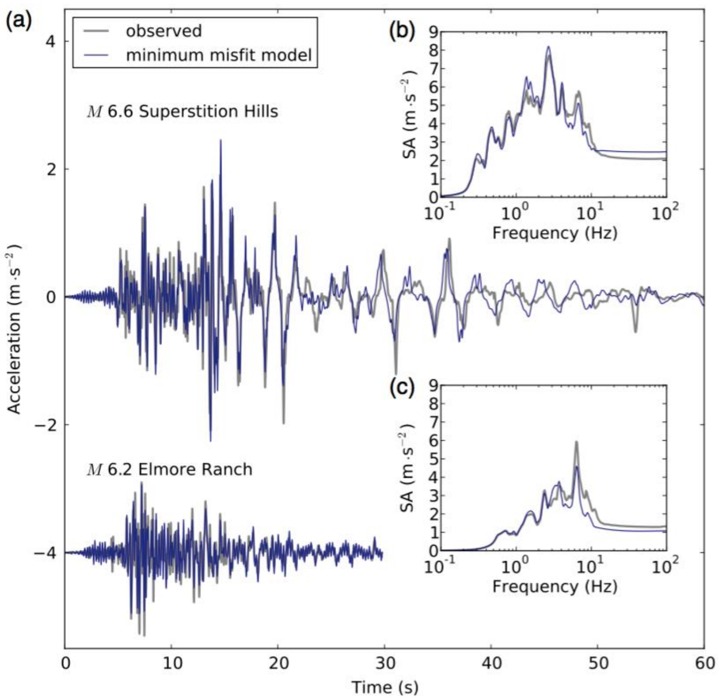

Figure 7. Comparison of observed surface time-series and spectral accelerations SA (gray) of the Mw 6.6 Superstition Hills earthquake and the Mw 6.2 Elmore ranch foreshock with minimum misfit solutions found from inversion (blue; modified from Roten et al., 2014).

An analogous approach to retrieve the dilatancy parameters can be based on direct CPTu measurements. In this case a liquefaction resistance curve (LRC) is computed from CPTu data using semi-empirical relations for each segment of the soil column. The LRC is defined as the number of cycles required to reach a horizontal shear strain of 3.75% (considered equivalent to 5% double amplitude axial shear in triaxial shear testing). The objective is to minimize the misfit between the observed LRC and the synthetic LRC derived from simulated laboratory tests. Both techniques represent an efficient way to calibrate the advanced constitutive model of Iai et al. (1995) based on direct *in situ* observations, allowing predicting pore-water pressure variations and the non-linear response of soft soils.

CONCLUSIONS

Geophysical site characterization has emerged over recent years as a crucial component of seismic hazard analysis. The emergence of ambient-noise measurement and processing techniques combined with spectral modelling of earthquake ground motion has provided cost effective methods that have brought forward significant advances in our understanding of the response and variability of the near-surface structure to earthquake ground motions. The use of non-ergodic (e.g. single-station sigma) variability in seismic hazard assessment has been hailed as the first significant reduction in uncertainty since PSHA was introduced. However, its use strongly relies on the explicit knowledge of site response, not only in the linear domain, but also at high strain levels. The further development and deployment of cost-effective site investigations will allow us to meet the conditions of defining reliable site-amplification together with single-station sigma not only for individual sites, but also on local or regional scales in the future.

The variety of different single-station and array techniques discussed in this paper complement one another, along with direct measurements of earthquake amplification at the sites of seismic networks, and the measurement of geotechnical properties for non-linear soil-response analyses. Bringing these techniques together has significantly improved our understanding of the site response for a variety of geological conditions, from sedimentary basins to unstable mountain slopes. Although site-characterization methods have been continuously developed over the last decade, there is still considerable potential for improvement. This particularly relates to the combination of multiple approaches including passive and active methods, together with numerical modelling of site-response and its comparison with empirical amplification derived from earthquake recordings. New approaches can improve seismic imaging of local structures including also those with strong lateral variations. Identification of 2D and 3D geometrical effects on the ground motion is key in site-specific seismic hazard analysis to avoid underestimation of the predicted ground motion.

Nonetheless, many issues are still open, and our methods are under intense and continuous development. Among other fields, the ongoing research on the micro-vibrations of slope instabilities, which includes extensive measurement campaign, is resulting in a globally unique database of unstable slope seismic responses. It will serve the monitoring of potential changes in the unstable rock masses and as a base for the interpretation of potential future landslides triggered by earthquakes.

REFERENCES

Aki, K. (1957). “Space and time spectra of stationary stochastic waves, with special reference to microtremors”, *Bull Earthquake Res. Inst. Tokyo Univ.*, **35**, 415-456.

Bard, P.-Y., Cadet, H., Endrun, B., Hobiger, M., Renalier, F., Theodulidis, N., Ohrnberger, M., Fäh, D., Sabetta, F., Teves-Costa, P., Duval, A.-M., Cornou, C., Guillier, B., Wathelet, M., Savvaidis, A., Köhler, A., Burjanek, J., Poggi, V., Gassner-Stamm, G., Havenith, H.B., Hailemikael, S., Almeida, J., Rodrigues, I., Veludo, I., Lacave, C., Thomassin, S., Kristekova, M. (2010). “From Non-invasive Site Characterization to Site Amplification: Recent Advances in the Use of Ambient Vibration Measurements”, *in: Garevski, M., Ansal, A. (Eds.), Earthquake Engineering in Europe. Springer Netherlands, Dordrecht*, pp. 105-123.

Bonilla, L. F., R. J. Archuleta, and D. Lavallee (2005). “Hysteretic and dilatant behavior of cohesionless soils and their effects on nonlinear site response: Field data observations and modeling”, *Bull. Seism. Soc. Am.*, **95** (6), 2373–2395.

Brenguier, F., Shapiro, N. M., Campillo, M., Nercessian, A., Ferrazzini, V. (2007). “3-D surface wave tomography of the Piton de la Fournaise volcano using seismic noise correlations”, *Geophysical research letters*, *34*(2).

Burjánek, J., G. Gassner-Stamm, V. Poggi, J.R. Moore, and D. Fäh (2010a). “Ambient vibration analysis of an unstable mountain slope”, *Geophys. J. Int.*, **180**, 820-828.

Burjánek, J., G. Gassner-Stamm, and D. Fäh (2010b). “Array-measurements in the area of Visp and St. Niklaus”, *COGEAR deliverable 3.1.2, Swiss Seismological Service, ETH- Zürich, SED/COGEAR/R/003/20100226*.

Burjánek, J., J.R. Moore, F.X. Yugsi-Molina, and D. Fäh (2012). “Instrumental evidence of normal mode rock slope vibration”, *Geophys. J. Int.*, **188**, 559-569.

Burjánek, J., B. Edwards, and D. Fäh (2014). "Empirical evidence of local seismic effects at sites with pronounced topography: A systematic approach", *Geophys. J. Int.*, **197**, 608–619.

Capon, J. (1969). "High resolution frequency wavenumber spectrum analysis", *Proc. IEEE*, **57**, 1408-1418.

Cauzzi, C., Edwards, B., Fäh, D., Clinton, J., Wiemer, S., Kästli, P., Cua, G. and Giardini, D. (2015). "New predictive equations and site amplification estimates for the next-generation Swiss ShakeMaps", *Geophys. J. Int.*, **200**, 421–438.

Cole, H. A. (1973), "On-line failure detection and damping measurement of aerospace structures by random decrement signatures", *NASA, Washington, D.C.*, Tech. Rep. CR-2205.

Danneels, G., Bourdeau, C., Torgoev, I., Havenith, H.B. (2008). "Geophysical investigation and dynamic modelling of unstable slopes: case-study of Kainama (Kyrgyzstan)", *Geophys. J. Int.*, **175**, 17-34.

Edwards, B., Michel, C., Poggi, V., & Fäh, D. (2013). "Determination of Site Amplification from Regional Seismicity: Application to the Swiss National Seismic Networks", *Seismological Research Letters*, **84**(4), 611–621.

Edwards, B., Ktenidou, O.-J., Cotton, F., Abrahamson, N., Van Houtte, C., & Fäh, D. (2015). "Epistemic uncertainty and limitations of the κ_0 model for near-surface attenuation at hard rock sites", *Geophys. J. Int.*,**202**(3), 1627–1645.

Ermert, L., Poggi, V., Burjnek, J. and Fäh, D. (2014). "Fundamental and higher two dimensional resonance modes of an Alpine valley", *Geophys. J. Int.*, **198**(2), 795811.

Fäh, D., Kind, F., Giardini, D. (2001). "A theoretical investigation of average H/V ratios", *Geophys. J. Int.*, **145**, 535-549.

Fäh, D., Kind, F., Giardini, D. (2003). "Inversion of local S-wave velocity structures from average H/V ratios, and their use for the estimation of site-effects", *Journal of Seismology*, **7**, 449-467.

Fäh, D., Stamm, G. and Havenith, H.-B., (2008). "Analysis of three-component ambient vibration array measurements", *Geophys. J. Int.*, **172**, 199–213.

Fäh, D., M. Wathelet, M. Kristekova, H. Havenith, B. Endrun, G. Stamm, V. Poggi, J. Burjánek and C. Cornou (2009). "Using ellipticity information for site characterization", *Neries deliverable JRA4 D4*, available at www.neries-eu.org

Gischig, V., G. Preisig, and E. Eberhardt (2015). "Numerical Investigation of Seismically Induced Rock Mass Fatigue as a Mechanism Contributing to the Progressive Failure of Deep-Seated Landslides", *Rock Mechanics and Rock Engineering*, 1-22.

Havenith, H.-B., Jongmans, D., Faccioli, E., Abdrakhmatov, K., Bard, P.-Y. (2002). "Site Effect Analysis around the Seismically Induced Ananevo Rockslide, Kyrgyzstan", *Bull. Seism. Soc. Am.*, **92**, 3190-3209.

Havenith, H.-B., Fäh, D., Polom, U., Roullé, A. (2007). "S-wave velocity measurements applied to the seismic microzonation of Basel, Upper Rhine Graben", *Geophys. J. Int.*, **170**, 346-358.

Hobiger, M., P.-Y. Bard, C. Cornou and N. Le Bihan (2009). "Single station determination of Rayleigh wave ellipticity by using the random decrement technique (RayDec)", *Geophys. Res. Lett.*, **36**, L14303.

Hobiger, M., C. Cornou, P.-Y. Bard, N. Le Bihan, W. Imperatori (2016). "Analysis of seismic waves crossing the Santa Clara Valley using the three-component MUSIQUE array algorithm", Submitted to *Geophys. Res. Lett.*

Iai, S., T. Morita, T. Kameoka, Y. Matsunaga, and K. Abiko (1995). "Response of a dense sand deposit during 1993 Kushiro-Oki earthquake", *Soils Found.*, **35**, 115–131.

Kind, F., Fäh, D., Giardini, D. (2005). "Array measurements of S-wave velocities from ambient vibrations", *Geophys. J. Int.*, **160**, 114-126.

Kleinbrod, U., J. Burjánek, and D. Fäh (2016). "On the seismic response of instable rock slopes based on ambient vibration recordings", *Proceedings of 5th IASPEI / IAEE International Symposium: Effects of Surface Geology on Seismic Motion (this volume)*, Taiwan.

Manea, E. F., Michel, C., Poggi, V., Fäh,D., Radulian, M., Balan (2016). "Improving the shear wave velocity structure beneath Bucharest (Romania) using ambient vibrations", *Geophys. J. Int.*, submitted.

Maranò, S., C. Reller, H.A. Loeliger and D. Fäh (2012). "Seismic waves estimation and wavefield decomposition: application to ambient vibrations", *Geophys. J. Int.*, **191**(1), 175-188.

Maranò, S., Fäh, D. and Y.M. Lu (2014). "Sensor placement for the analysis of seismic surface waves: sources of error, design criterion and array design algorithms", *Geophys. J. Int.*, **197**, 1566–1581.

Maranò, S., M. Hobiger, and D. Fäh (2016a). "Retrieval of Rayleigh wave ellipticity from ambient vibration recordings", *Geophys. J. Int.* submitted.

Maranò, S., M. Hobiger, and D. Fäh (2016b). "Analysis of Rayleigh waves with circular wavefront: a maximum likelihood approach", *Geophys. J. Int.*, submitted.

Michel, C., Edwards, B., Poggi, V., Burjánek, J., Roten, D., Cauzzi, C., Fäh, D. (2014). "Assessment of Site Effects in Alpine Regions through Systematic Site Characterization of Seismic Stations", *Bull. Seism. Soc. Am.*, **104**(6), 2809–2826.

Michel, C., Fäh, D., Cauzzi, C., Edwards, B. (2016). "Site amplification at the city scale in Basel (Switzerland) from geophysical site characterization and spectral modelling of recorded earthquakes", *Physics and Chemistry of the Earth*, submitted.

Moore, J.R., V. Gischig, J. Burjánek, S. Loew, and D. Fäh (2011). "Site effects in unstable rock slopes: dynamic behavior of the Randa instability (Switzerland)", *Bull. Seism. Soc. Am.*, **101**, 3110-3116.

Nakamura, Y. (1989), "A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface", *Quarterly reports of the Railway Technical Research Institute Tokyo*, **30**, 25-33.

Picozzi, M., Parolai, S., Bindi, D., Strollo, A. (2009). "Characterization of shallow geology by high-frequency seismic noise tomography", *Geophys. J. Int.*, **176**(1), 164-174.

Pilz, M., Parolai, S., Picozzi, M., Bindi, D. (2012). "Three-dimensional shear wave velocity imaging by ambient seismic noise tomography", *Geophys. J. Int.*, **189**(1), 501-512.

Pilz, M., Parolai, S., Bindi, D. (2013). "Three-dimensional passive imaging of complex seismic fault systems: evidence of surface traces of the Issyk-Ata fault (Kyrgyzstan)", *Geophys. J. Int.*, ggt214.

Pilz, M., Parolai, S., Bindi, D., Saponaro, A., Abdybachaev, U. (2014). "Combining seismic noise techniques for landslide characterization", *Pure and Applied Geophysics, 171*(8), 1729-1745.

Poggi, V., and D. Fäh (2010). "Estimating Rayleigh wave particle motion from three-component array analysis of ambient vibrations", *Geophys. J. Int.*, **180**(1), 251-267.

Poggi, V., Edwards, B., Fäh, D. (2011). "Derivation of a Reference Shear-Wave Velocity Model from Empirical Site Amplification", *Bull. Seism. Soc. Am.*, **101**(1), 258–274.

Poggi, V., Fäh, D., Burjanek, J., Giardini, D. (2012). "The use of Rayleigh-wave ellipticity for site-specific hazard assessment and microzonation: application to the city of Lucerne, Switzerland", *Geophys. J. Int.*, **188**, 1154-1172.

Poggi, V., Ermert, L., Burjanek, J., Michel, C. and Fäh, D., (2015). "Modal analysis of 2D sedimentary basin from frequency domain decomposition of ambient vibration array recordings", *Geophys. J. Int.*, **200**, 615626.

Renalier, F., Jongmans, D., Campillo, M. and Bard, P.-Y., (2010). "Shear wave velocity imaging of the Avignonet landslide (France) using ambient noise cross correlation", *J. Geophys. Res.*, **115**, F03032, doi:10.1029/2009JF001538.

Roten, D., Fäh, D., Cornou, C., Giardini, D. (2006). "Two-dimensional resonances in Alpine valleys identified from ambient vibration wavefields", *Geophys. J. Int.*, **165**, 889-905.

Roten, D., Fäh, D., Olsen, K.B., Giardini, D. (2008). „A comparison of observed and simulated site response in the Rhône valley", *Geophys. J. Int.*, **173**, 958-978.

Roten, D., D. Fäh, L. F. Bonilla, S. Alvarez-Rubio, T. M. Weber, and J. Laue (2009). "Estimation of non-linear site response in a deep Alpine valley", *Geophys. J. Int.*, **178**(3), 1597–1613.

Roten, D., D. Fäh, and L. F. Bonilla (2013). "High-frequency ground motion amplification during the 2011 Tohoku earthquake explained by soil dilatancy", *Geophys. J. Int.*, **193**(2), 898–904.

Roten, D., D. Fäh, and L. F. Bonilla (2014). "Quantification of Cyclic Mobility Parameters in Liquefiable Soils from Inversion of Vertical Array Records, *Bull. Seism. Soc. Am.*, **104**(6), 3115–3138.

Wathelet, M., D. Jongmans and M. Ohrnberger (2004). "Surface wave inversion using a direct search algorithm and its application to ambient vibration measurements", *Near Surface Geophysics*, **2**, 211-221.