Chapter 5
From Non-invasive Site Characterization to Site Amplification: Recent Advances in the Use of Ambient Vibration Measurements

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Abstract A series of investigations has been carried out over the last decade in Europe aimed at deriving quantitative information on site amplification from non-invasive techniques, based principally on surface wave interpretations of ambient noise measurements. The present paper focuses on their key outcomes regarding three main topics. First, methodological, hardware and software developments focusing on the acquisition and the processing of both single point and array microtremor measurements, led to an efficient tool with in situ control and processing, giving rise to robust and reproducible results. A special attention has been devoted to the derivation and use of the Rayleigh wave ellipticity. Second, the reliability of these new tools has been assessed through a thorough comparison with borehole measurements for a representative – though limited – set of sites located in Southern Europe, spanning from stiff to soft, and shallow to thick. Finally, correlations between the site parameters available from such non-invasive techniques, and the actual site amplification factors as measured with standard techniques, are derived from a comprehensive analysis of the Japanese KIKNET data. This allows to propose alternative, simple site characterization providing an improved variance reduction compared with the "classical" V_{S30} classification. While these results could pave the road for the next generation of building codes, they can also be used now for regulatory site classification and microzonation studies, in view of improved mapping and estimation of site amplification factors, and for the characterization of existing strong motion sites.

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5.1 Introduction

Shear wave velocity is the most important material property controlling amplification phenomena during earthquakes, and the need for reliable, affordable site survey techniques has been often emphasized in engineering seismology. Amongst a wide variety of direct applications, one may mention the drastic lack of quantitative information on subsurface structure for most of seismic stations in the EURO-MED area, microzonation studies at the city scale (i.e., from a few to 100 km^2), and the identification of site classes as required by building codes. Such survey techniques should combine cost efficiency and physical soundness in order to provide reliable, quantitative estimates of the relevant site parameters over wide areas or numerous sites.

In that aim, the use of ambient noise recordings is indeed very appealing: its non-invasive character makes it well suited for dense urban environments, the required equipment (sensitive seismometers and data acquisition systems) is available at affordable cost, and the processing techniques have been the topic of many developments in recent years. However, the wide variety of processing techniques (from very simple to highly sophisticated), and the existence of different interpretation viewpoints (for instance on the use of H/V information) results in legitimate questions and doubts in both geotechnical and end user communities.

Given this background situation, a series of investigations has been launched over the last decade in Europe in order to explore the actual capabilities of noise-based techniques in view of deriving quantitative information on site amplification. This has been achieved mainly within the framework of two European projects: SESAME (Site Effects aSsessment from AMbient noisE, a FP5 project # EVG1-CT-2000-00026, 2001–2004, see Bard et al., 2004) and NERIES – JRA4 (NEtwork of Research Infrastructures for European Seismology, a FP6 I3 project # RII3-CT-2006-026130, 2006–2010), with complementary funding from various national projects and agencies in France, Germany, Greece, Italy, Portugal, Switzerland and Turkey. It included methodological, hardware and software developments, which led to an efficient tool combining in situ control and preliminary processing, with robust and reproducible results. It also included a comprehensive data analysis in order to derive statistically meaningful correlations between site amplification characteristics and the site parameters that can reliably be derived from such non-invasive, noise-based techniques. The following sections briefly summarize the main outcomes of this work, addressing successively the software and hardware developments, a careful comparison with results of borehole soundings for a representative series of sites, and the derivation of correlations between site amplification factors and site parameters.

5.2 Array Measurements and Processing of Ambient Vibrations

The base idea schematically illustrated in Fig. 5.1 is to deploy temporary, small aperture (typically from a few meters up to kilometric scale), 3-component, high sensitivity seismological arrays, to record the ambient vibrations, to extract the

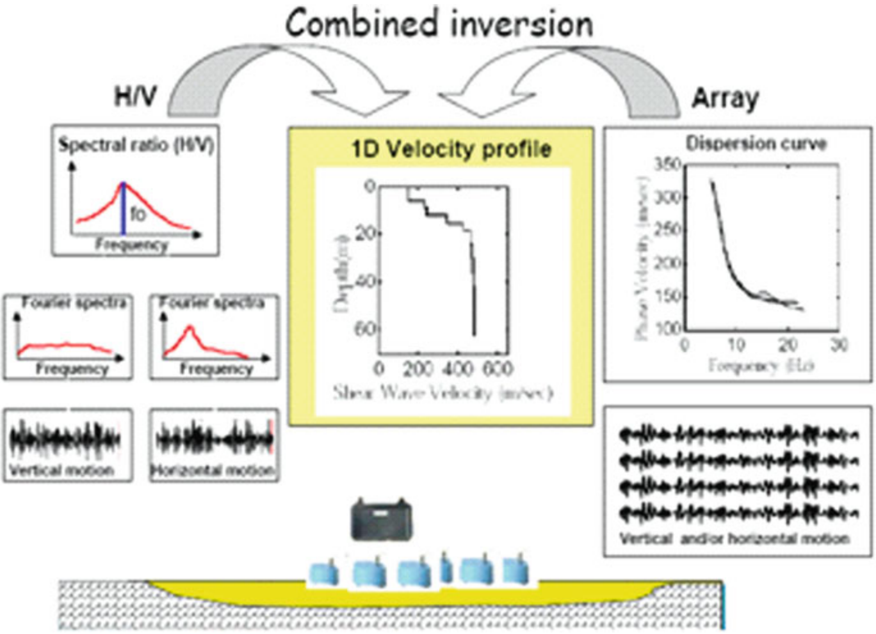

Fig. 5.1 Principle of H/V and array processing

dispersion characteristics of Rayleigh – and possibly Love – waves, from which to derive either detailed velocity profiles or average velocity values. These ambient vibration measurements may also be complemented with active measurements (MASW[1] type, cf. Park et al., 1999) allowing a better resolution of very shallow layers, while the array processing is also usefully enlightened by the classical H/V analysis. Recent developments addressed improvements in both hardware and software tools to help the field and processing work, and methodological developments as well to investigate new, complementary processing techniques.

5.2.1 Hardware

The target is to perform wireless, synchronous recording of microtremors on 10 m to 1–2 km wide arrays within urban environments, with real time array processing for in situ control. About a decade ago, there did not exist any equipment meeting these requirements. A series of hardware developments and tests were thus carried out, first by the Potsdam University group (F. Scherbaum, M. Ohrnberger, D. Vollmer), and later in Grenoble (M. Wathelet), ITSAK (A. Savvaidis, N. Theodulidis, H. Cadet), and SED-ETHZ (D. Fäh, J. Revilla, S. Marano, V. Poggi). In the early

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[1] Multi-channel analysis of surface waves.

phase of the project (2006–2008), the developed hardware (thanks to a national, complementary funding at U. Potsdam), was fully dedicated to array measurements of ambient vibrations. All measurements at all European sites (about 25 in total, see the next section) were performed with this instrumentation. Later however, acknowledging the fact that the total cost of this specific tool could look prohibitive, new reflections were initiated to design an alternative "add-on" system that could be implemented on existing mobile seismological stations at a much lower cost, and provide the same field efficiency and user-friendliness without altering reliability and robustness. Prototypes have been developed at LGIT and UP; their cost is about 1,000 Euros/station. It includes precise, real time GPS positioning, wireless automatic meshing and data transmission to a central unit, and it is flexible enough to fit different acquisition systems. However, the technology is evolving extremely rapidly, and manufacturers of seismic stations are now proposing material – or announce it for very soon – that meets some – not always all – of the above requirements; the proposed costs remain nevertheless significantly higher than plain seismic stations.

5.2.2 Software

The target was to develop and document reliable software tools to derive shear wave velocities from non-invasive, surface measurements (microtremor array recordings as well as active MASW recordings). This requires (a) to extract the dispersion characteristics (DC) of Rayleigh and Love waves, and (b) to derive either detailed velocity profiles or average velocity values from DC curves or SPAC (Spatial Autocorrelation) processing.

Retrieving reliable information from complex ambient vibrations is indeed a non-trivial issue, which is not satisfactorily addressed by most of the black-box software packages already available on the market. Their main limitations are basically two-fold:

- the use of one single, specific array processing technique to derive the dispersion curves DC (ex.: FK only, or SPAC only) does not allow cross-checking which is always useful in ambiguous cases;
- the inversion part (deriving velocity profiles from DC) generally neglects, or at best only poorly addresses, the non-uniqueness of solutions. This is very often witnessed by the apparent high-resolution of the resulting profiles, with rather thin layers often including one or several velocity inversions at depth: this is an easy, but highly non unique, way to reach an excellent fit with measured DC, which however proves most often to be fictitious.

As a consequence, a specific, multiplatform software tool, named "geopsy", was developed, which has now reached a satisfactory maturity level, and is freely available on line (http://www.geopsy.org). Its development first emerged as a side product of the SESAME project especially between LGIT and University of Potsdam. The initial objective of this joint effort has been to centralize in one unique framework all state-of-the-art techniques for processing ambient vibrations and to provide the tools for their necessary integration. Very rapidly however, though built around ambient vibrations, its design was extended to cover most of the non-invasive methods used in site characterization: for instance, refraction and active surface wave experiments. With the NERIES project, geopsy has evolved a lot, including a number of new modules developed with a graphical user interface, and also accepting real-time feeding with data streams for *in situ* checks. The array processing modules include standard and high resolution frequency-wavenumber analysis (“FK”/“HRFK”: Capon, 1969; Lacoss et al., 1969), spatial autocorrelation analysis (“SPAC”: Aki, 1957; Bettig et al., 2001; Köhler et al., 2007; Ohrnberger et al., 2004, 2005), active body and surface wave experiments (reflection, refraction, MASW, see Renalier, 2010). All techniques may be applied to 3-component recordings, therefore addressing Love waces as well as Rayleigh waves. The inversion module is based on the neighborhood algorithm proposed by Sambridge (1999), with various adaptations and improvements as detailed in Wathelet et al. (2004, 2005, 2008) and Wathelet (2008), Di Giulio et al. (2006); a special attention has been devoted to the non-uniqueness of solutions and to the sensitivity to the initial model parameterization, which led to various recommendations : combining inversions using different types of information, using a-priori knowledge whenever available, visualizing the uncertainties on velocity profiles, balancing the model complexity with the gain in misfit reduction through the Akaike information criteria (Akaike, 1974; Savvaidis, 2009). A more detailed description of the above-mentioned developments and improvements can be found in the referenced papers, with a global synthesis in the deliverable D9 of the NERIES-JRA4 project (Fäh et al., 2010). An open source model has been definitely adopted for the distribution of these codes, which lets all doors open for further developments and improvements. Open source and free accessibility offer a quick distribution to a wide community world-wide which in turn accelerates the debug and stabilization processes (variety of environments and user opinions).

The NERIES project thus allowed to transform the geopsy package from a small software distributed within a limited group of highly specialized research and industrial individuals, into a reference software distributed all around the globe in a wide range of scientific and engineering communities. Substantial efforts were made to include more processing techniques and to integrate them in a comprehensive package.

In parallel, considering the complexity of this versatile software, extended training 1-week long seminars are organized around the world to teach ambient vibration fundamentals and explain how to use geopsy in this context. The corresponding course material is presently being used as a basis for an in-depth documentation to be distributed with the software, and is completed by an on-line wiki – type documentation.

5.2.3 Derivation and Inversion of Rayleigh Wave Ellipticity

The derivation of dispersion curves with these array techniques needs however a large number of seismic sensors and is somewhat time-consuming (e.g., ½–1 day of field work per site). It is therefore tempting to search for simpler alternatives. The ellipticity of Rayleigh waves, i.e. the ratio between the horizontal and the vertical movement, strongly depends on the local soil structure (e.g. Fäh et al., 2001). As a result, it can be inverted to retrieve the underground structure, i.e., the shear wave velocity profile and sediment thickness. Special attention was thus devoted to attempts to extract Rayleigh wave ellipticity from single point or array, 3-component measurements, and to its direct inversion in terms of velocity profile.

Two methods were proposed and tested during the NERIES project for retrieving ellipticity from single-station measurements. The first method was initiated during the SESAME project and is based on time-frequency analysis with continuous wavelet transform. It reduces the SH-wave influence by identifying P-SV-wavelets along the signal and computing the spectral ratio from these wavelets only. The second method is the so-called "RAYDEC" technique (Hobiger et al., 2009a; Fig. 5.2), which is adapted from the random decrement technique commonly used to characterize dynamic parameters of buildings, and is indeed tightly connected with the autocorrelation analysis (see Asmussen, 1997 for a comprehensive review). It is basically looking for the optimal cross-correlation between the vertical motion and one direction of horizontal component, with due consideration for the fact that for Rayleigh waves, vertical and horizontal components exhibit a 90° phase shift.

Tests on synthetic noise with both single station methods proved very encouraging, with resulting ellipticity estimates much closer to the theoretical ones than the raw H/V curves. Reliable results were obtained for the right flank of the H/V curve, between the first peak at the fundamental frequency of resonance and the first trough at higher frequency. The procedures eliminate efficiently most of the Love and body wave contributions.

As ellipticity alone cannot fully constrain the velocity profile, it has to be coupled with some scaling measurements, for instance MASW or small aperture SPAC, which allow to estimate the very shallow velocity. A few test applications on real data sets also proved very encouraging when compared with "classical" array analysis (Hobiger et al., 2010).

For recordings of ambient vibrations on large arrays, there are two ways to retrieve ellipticity information. Such techniques were developed within the NERIES project. The first strategy curves considers a reduction factor to be applied on the raw H/V ratio, so as to eliminate the contribution of Love waves on the H component (see Bonnefoy-Claudet et al., 2008). This ratio is related to the Rayleigh/Love wave ratio that can be derived from three-component SPAC analysis (Köhler et al., 2007) as a function of frequency. A combination with the H/V curve computed by the classical method (simple spectral ratios) should then produce a good estimate of the Rayleigh wave ellipticity. The second strategy proposed by Poggi and Fäh (2010) is using high-resolution frequency-wavenumber array analysis. The technique is applied to the three components of motion and is based on the assumption that amplitude

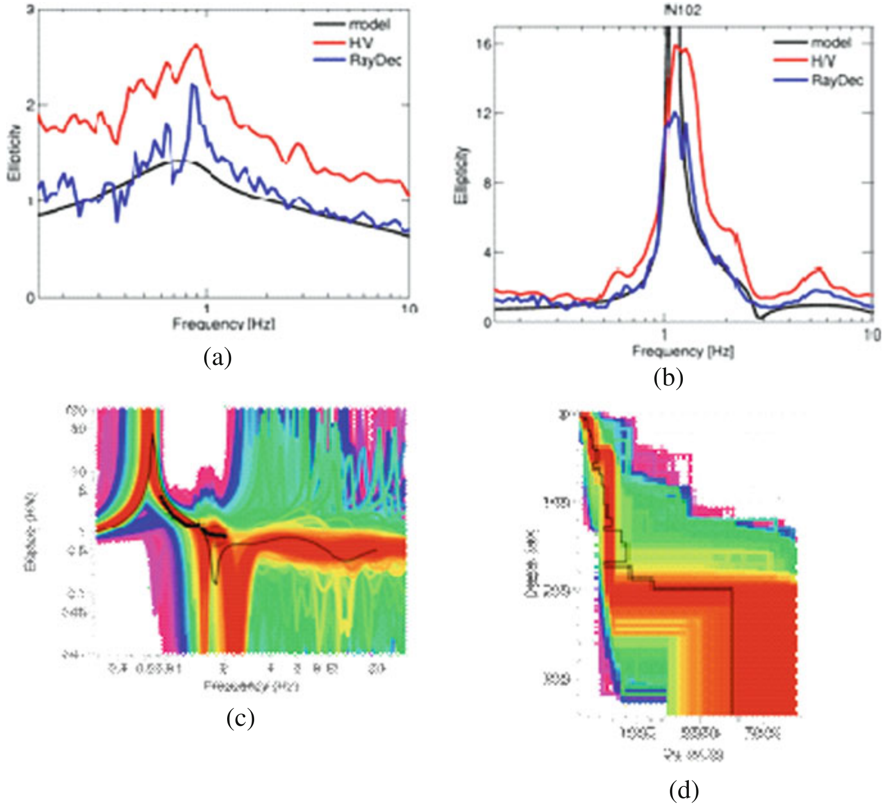

Fig. 5.2 Example use of ellipticity for velocity profile inversion. The *top* two plots (Hobiger et al., 2009b) display, for two cases with a moderate (*left*, **a**) and large (*right*, **b**) impedance contrast the comparison between the actual Rayleigh wave ellipticity (*black curve*), the H/V curve derived from a standard processing (*red*) and the estimated ellipticity with the RAYDEC method (*blue*). The *bottom* plots (Hobiger et al., 2010) display an example inversion of ellipticity using additional information to constrain the shallow velocity: the continuous broad band *black curve* represents the theoretical ellipticity (**c**, *left*) and the actual velocity profile (**d**, *right*), the limited band *black curve* with *vertical bars* represent the estimated ellipticity and its uncertainty used for the inversion, and the *colored curves* display the ellipticity (*left*) for many inverted velocity profiles (*right*); the *red color* corresponds to the lower misfit, while other *colors* correspond to increasing misfit values, from *yellow* to *magenta* through *green* and *blue*

maxima in the f-k cross-spectrum must represent the true power amplitude of the corresponding signal. In the case of Rayleigh waves, the ratio between maxima obtained from the horizontal (radial-polarized) and vertical components of motion will thus also represent the frequency-dependent ellipticity function. Consequently, if the Rayleigh dispersion curves of the different modes can be identified on the f-k plane, then the corresponding modal ellipticity patterns can also be separated and extracted. This second method also offers the possibility of estimating the

Rayleigh/Love ratio. Testing all these single-station and array methods in real cases is part of on-going research, and not yet implemented in the geopsy software.

5.3 Testing of Ambient Vibration Array Techniques

The present state of practice in geotechnical engineering considers borehole techniques (i.e., Cross-hole – “CH”–, Down-hole – “DH” –, and sonic logging), as the “ground truth”, i.e. the most widely accepted survey techniques. Even though the results of such borehole investigations do include some non-negligible uncertainties related to both the measurement and the processing/interpretation steps, any new technique needs to be validated through a comparison with the well-established practice. Therefore, the careful testing and comparison with standard borehole techniques was considered a key issue for an objective assessment of the reliability of these non-invasive techniques and tools.

5.3.1 Technical and scientific considerations

A first step was achieved in 2006 with the organization of a blind test (ESG2006, Cornou et al., 2009) about the retrieval of velocity profiles from array recordings. The main learnings have been the very good consistency of all derived dispersion curves (they agreed within ±10% in most cases), contrasting with the much larger variability of the inverted velocity profiles, in relation with (a) the difficulties of proper mode identification and (b) the very heterogeneous quality of inversion algorithms.

The second step was carried out within the NERIES project. A set of about 20 representative sites was selected in Italy, Greece and Turkey, spanning from stiff to soft, and thick to shallow, for which prior borehole velocity measurements – either CH or DH, or sometimes both – were available (Fig. 5.3a). Ambient vibration (AMV) array measurements were performed together with active seismics (refraction and MASW) at each site. The specific scientific targets were:

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Fig. 5.3 (continued) Comparison between non-invasive techniques and borehole measurements. *Top* **a** location of measured sites. *Bottom left* **b** ratio between the borehole velocity profiles and admissible inverted profiles, for all sites; *Bottom right* **c** comparison of V_{S30} values from borehole (abscissa) and the range of values derived from non-invasive techniques (ordinate). *Top* **d** Range of dispersion curves obtained with different non-invasive techniques (FK, SPAC, MASW) as mapped in the (velocity/wavelength) plane. The *red* (resp., *green*) *horizontal lines* correspond to maximum (resp., minimum) wavelengths; *Bottom left* **e** comparison between the V_{S30} ranges derived from admissible inverted profiles and the range of phase velocities $V_{\lambda 30}$ corresponding to a wavelength of 30 m (*upper dotted black line* on Fig. 5.3d); *Bottom right* **f** similar comparison between $V_{\lambda 30}$ and V_{S30} derived from borehole measurements

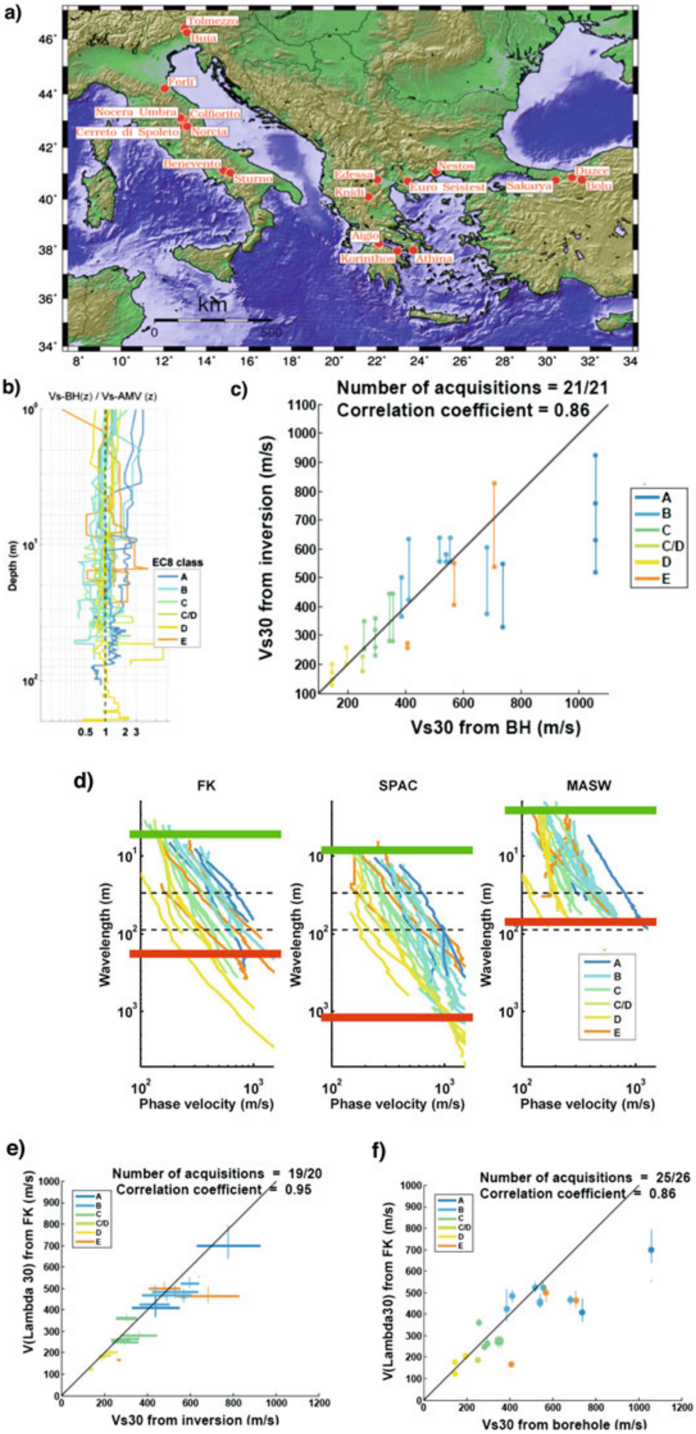

Fig. 5.3 (continued)

- to assess the validity of the AMV technique by comparing it to borehole measurements and to Multichannel Analysis of Surface Waves (MASW);
- to evaluate the typical wavelength ranges derived by the different methods;
- to evaluate the necessity and sensitivity of the inversion for the evaluation of V_{Sz} (time-averaged velocity down to depth z).

In order to stay affordable and feasible, active seismic experiments involved 24–4.5 Hz geophones (both horizontal and vertical) for recording the signals generated with hammer and plate (the use of explosives or Vibroseis was deliberately avoided because of the practical and logistic difficulties in urban environments), with 24–115 m long lines. They were analyzed with the MASW technique to compute the dispersion curves. Passive seismic was acquired with 8 stations linked with wireless connections and monitored with near real-time processing software allowing the on site adaptation of the acquisition. Dispersion curves were computed both with the frequency wave-number (FK) and with the Spatial AutoCorrelation (SPAC) techniques for Rayleigh and Love waves. They were inverted with the neighborhood algorithm as implemented in the geopsy software. Measured dispersion curves and admissible inverted Vs profiles, together with V_{S30} values, were finally compared to results of borehole tests available at all Italian and Greek sites, and to previous MASW results at Turkish sites.

The answers to the targeted questions are summarized below:

- The comparison proved good for all sites with V_{S30} lower than 500 m/s; at stiffer sites, velocity values estimated with surface wave techniques (both passive and active) are smaller than those derived from boreholes measurements (Fig. 5.3b, c). This trend is consistent with the previous comparison results reported by Moss (2008). Incidentally, one outcome of the non-invasive techniques with the geopsy processing is to provide an estimate of the measurement uncertainties, indicated by the error bars in Fig. 5.3c.
- Minimum and maximum wavelengths are in average around 10 and 1,000 m for the array measurements, and are around 6 and 45 m for MASW (Fig. 5.3d). With the same array geometry, SPAC processing generally allows to reach larger depth than FK processing, which in turn allows a better resolution of shallow wavelengths. The corresponding penetration depths, corresponding to about one-third to one half of the maximum wavelength, are typically in the range 10–30 m for MASW, while they exceed 100 m for most of AMV cases, and often 200 m. This is to be compared to the borehole depths, typically of a few tens of meters, with a cost significantly increasing with depth. The analysis of the high frequency part of DC, corresponding to shallow velocities, showed that the AMV Rayleigh wave results were good at high frequencies, especially from FK techniques. Even though Love waves estimated from AMV and MASW covered complementary frequency ranges, including the MASW Love wave dispersion curve did not improve much the inversion results because of the good performance of FK processing at high frequency.
- Considering the fact that inversion step is the most tricky one, it is useful to look for ways to skip it, at least for a site classification purpose. The starting point is

again to map the dispersion curves in the (Rayleigh wave velocity/wavelength) plane displayed in Fig. 5.3d. One may directly compare the measured Rayleigh wave velocity corresponding to a wavelength of 30 m (Vλ30), and the VS30 values derived either from inverted velocity profiles (Fig. 5.3e), or from borehole measurements (Fig. 5.3f). The correlation between Vλ30 and VS30 derived from inversions proved rather good; indeed, when considering larger data sets, the best correlation with inverted VS30 is observed when considering Vλ40 or Vλ45 (Cornou, personal communication; Zor et al., 2010): this indicates that the inversion step, which is the most subjective, is not needed to derive VS30 values. The correlation between Vλ30 and borehole estimates of VS30 thus exhibits the same characteristics as discussed above and displayed on Fig. 5.3c, i.e., a good agreement for soft and intermediate sites (VS30 < 500 m/s), and an underestimation trend for stiff sites (VS30 > 600 m/s). However, given the limited size of the site sample considered here, these trends should be considered only as indicative and should be checked with further studies.

- Finally, another valuable outcome of this series of measurements concerns the robustness of the results. As detailed in Endrun et al. (2009), array microtremor measurements performed on the same sites at different periods (day, night, different years and seasons) by different teams with different instruments, did yield the same dispersion characteristics. In addition, even though a wide variety of individual velocity profiles are compatible with these dispersion curves, the estimates of average parameters such as V_{S30} also exhibit a very satisfactory robustness whatever the implicit or explicit assumptions considered in the inversion step.

The difference for stiff sites is somewhat intriguing, and can have several origins:

- the first one is the frequency range of the measurements: borehole techniques provide S-wave velocities for high-frequency/short wavelength waves (typically 500 Hz to 1 kHz for cross-hole techniques, and 100–300 Hz for down-hole techniques), while non-invasive techniques operate in the engineering seismology frequency range, i.e. typically 0.5–20 Hz. The "effective propagation medium" may therefore greatly differ from one technique to the other, since low frequency techniques sample larger wavelengths and may be affected by intermediate-size heterogeneities (fractures, joints, . . .) which are not affecting short distance travel times. Examples of such differences are mentioned in Havenith et al. (2002). In such a case, wave velocities identified from non-invasive techniques should be more representative of the actual dynamic behavior during earthquakes, because of the more appropriate frequency range of the measurements.
- the second one – which is linked to the first one – is the volume sampled by each technique: borehole techniques represent essentially point measurements, while non-invasive, surface measurements represent average velocities over tens to hundreds of meters. While the spatial and depth resolution is without any doubt much finer for borehole techniques than for surface-wave techniques, the averaging effects of the latter provide a very complementary image of the subsoil, at a much more affordable cost than the multiplication of borehole measurements.

5.3.2 Cost Considerations

Another important topic for comparison between invasive (borehole) and non-invasive surface wave techniques is the cost.

The needed equipment for ambient vibration measurements now amounts to about 60–80 k Euros for a complete array system consisting of 8–10 sensors, an acquisition system, wireless connexions and a precise positioning system. At least half of this cost corresponds to intermediate to broad band, sensitive sensors. There is presently no fully suited material available from the manufacturers; would this type of measurements become a routine engineering practice, one may anticipate a significant cost decrease. This is slightly to significantly more expensive than a MASW 24–48 sensor equipment, but it allows to reach much larger depths (see Fig. 5.3d). This amount should be compared with the equipment cost required by borehole techniques, consisting in the drilling device (generally installed on a truck), and the borehole tool (including the processing software).

The most important component is the marginal cost of measurements, which is mainly consisting in work days. Borehole techniques typically require 1 day of work for 2 persons simply for drilling down to 30 m, which thus results in 4–6 work-days for the cross-hole technique (depending on whether 2 or 3 close boreholes are used), and 2 for the down-hole one, followed by another 3 work days for the measurements and routine processing. Non-invasive techniques, especially ambient vibration array techniques, require slightly more time for the measurement and processing (about 4 work days), but do not need any preparatory work. As a consequence, even though the initial equipment cost is still more expensive than borehole equipment, the measurement cost is significantly lower, especially when compared with cross-hole techniques.

5.4 Usefulness for Routine Applications: Derivation of Noise-Compatible Site Amplification Prediction Equations (SAPE)

Over the last decade, the site classifications used in seismic regulations have been increasingly based on the use of the V_{S30} parameter, following the works of Borcherdt (1994) and colleagues in the early nineties. However, many seismologists and engineers (e.g., Mucciarelli and Gallipoli, 2006; Castellaro et al., 2008) have expressed some reluctancy since this single parameter does not capture the physics of 1D site amplification, even in the simple 1D case: the amplification characteristics should indeed be related both to the impedance contrast between the shallow soil and the underlying bedrock (and also to the damping characteristics), and to the thickness of the surface layers. As a consequence, the single parameter V_{S30} can only be considered as a proxy to such more physical parameters, and its correlation to the actual amplification characteristics should therefore be at least adjusted regionally to correspond to the local geology. This adaptation work is nevertheless only rarely performed, mainly because of the lack of reliable data (absence of strong motion recordings, or missing geotechnical information on recording sites).

The simplicity of this site classification, its satisfactory performance on the original available data, together with the relative low cost of the background site survey (SPT down to 100 ft/30 m which could be performed within 1 day), made it very popular and led to its spreading in many earthquake regulations throughout the world, since no alternative could be proposed combining cost effectiveness, simplicity, and physical relevance. This challenge is addressed here as a continuation of the previous developments on noise-based site surveys, by investigating the correlations between some alternative, twin-parameter site categorization that may be derived from non-invasive techniques, and the site amplification factors on high quality data.

The work briefly summarized here is described in more detail in Cadet (2007) and Cadet et al. (2008, 2010a, b, c): it involved an extensive analysis of a subset of the Japanese KIKNET data consisting of about 4,000 3-component recordings from a total of 375 sites. Only events with a moment magnitude (Mw) higher than 4.0 and a depth less than 25 km were considered. The range of hypocentral distances for the selected records is 0.5–343 km and the range of magnitudes (Mw) is 4–7.3. The range of recorded peak ground acceleration PGAs is 0.4–927 cm/s^2. The records were band-passed filtered between 0.25 and 25 Hz (Pousse, 2005).

The investigated site parameterization is based on the time-averaged shear wave velocity over the top z meters, V_{Sz}, and the site fundamental frequency f_0. V_{Sz} parameters were derived for the KIKNET sites from the measured velocity profile (down-hole technique) for four different depths (z = 5, 10, 20 and 30 m), while the fundamental frequency was obtained from surface to down-hole spectral ratios, and checked for consistency both with the theoretical 1D transfer function based on the down-hole velocity profile, and the surface H/V ratios. As displayed on Fig. 5.4, these two parameters are shown to be complementary and to provide independent information on the overall impedance contrast or shallow soil softness

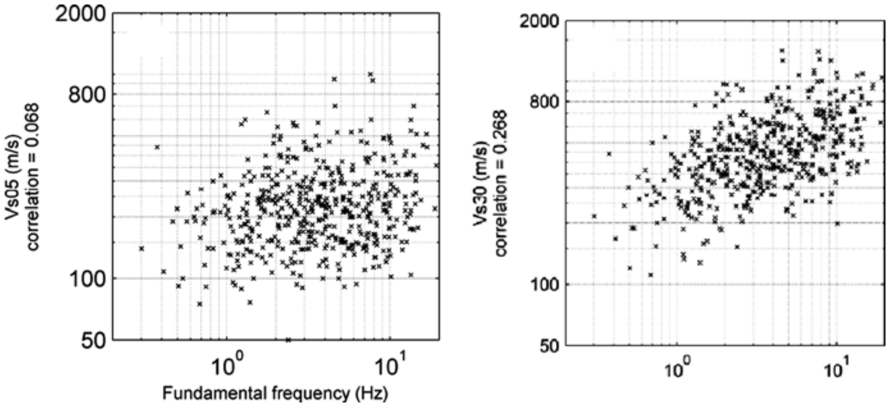

Fig. 5.4 Distribution of the considered KIKNET site set in the (f_0, V_{S05}) and (f_0, V_{S30}) planes, (*left* and *right*, respectively)

(V_{Sz}), and the overall thickness of the surface layers responsible for the amplification (f_0). Most importantly, both parameters may be derived in a robust and inexpensive way from single point ambient noise measurements (H/V processing, Haghshenas et al., 2008), and array microtremor processing or even SASW/MASW techniques for very shallow V_{Sz}, i.e., V_{S05}, V_{S10} and sometimes V_{S20}.

The site amplification factors were derived empirically from the average surface/downhole ratios between response spectra (BHRSR): considering the wide scatter in the S-wave velocities and depths of down-hole sites (300–3,300 m/s, 8–900 m), a correcting procedure was established with two main goals:

- to normalize the raw BHRSR ($BHRSR_{raw}$ in Fig. 5.5b) to a standard reference corresponding to the "generic rock profile" proposed by Boore and Joyner (1997) with $V_{S30} = 800$ m/s,
- and to remove high frequency amplification artefacts associated with the location of reference sites at depth.

More details can be found in Cadet et al. (2010b) on this impedance and depth correction procedure. As displayed in Fig. 5.5b, the so corrected $BHRSR_{cn}$ values exhibit a significantly reduced scatter compared to the original amplification factors $BHRSR_{raw}$.

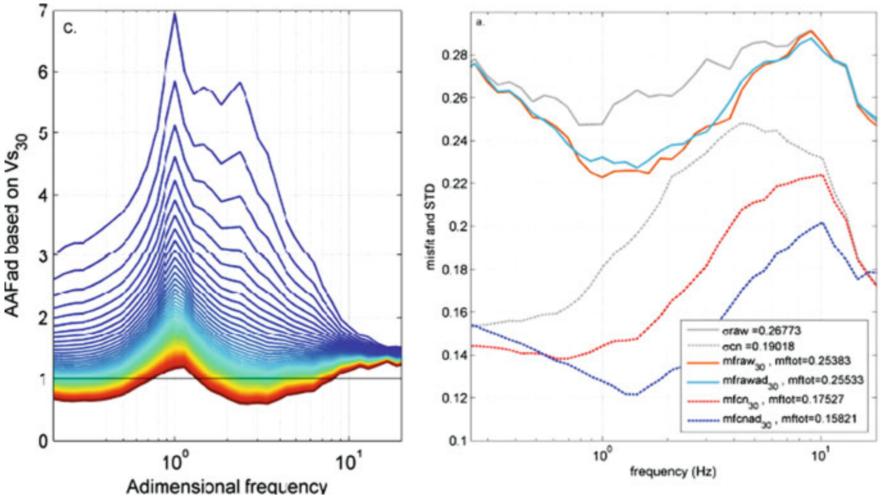

Fig. 5.5 Example results on new site amplification prediction equations ("SAPE", adapted from Cadet et al., 2010c) derived from KIKNET data. *Left*: dependence of the amplification function on the dimensionless frequency and V_{S30} (color code on *left side*, related to V_{S30} value). *Right*: Comparison in the real frequency space between standard deviation of the initial family $BHSR_{raw}$ (*gray*), standard deviation of the corrected $BHSR_{cn}$ family (*dot gray*, with correction for depth and impedance). The misfit obtained by correlating raw (*solid line*) and corrected (*dotted line*) BHSR to V_{S30} only and to the couple (V_{S30}, f_0) are shown in *blue* and *orange*, respectively)

The final step consisted in establishing correlations between these corrected amplification factors and the site parameters $V_{Sz,i}$ and f_0,$_i$ for all sites i. This correlation has been performed in two steps (Cadet et al., 2010c):

1. the corrected amplification functions were first expressed as a function of dimensionless frequency $\nu = f/f_{0i}$. The underlying idea is that, when $f < f_{0i}$, the amplification should remain small, while it should be significantly larger around f_{0i}, and more scattered for $f > f_{0i}$. It results in new, "shifted" amplification functions $A_i(\nu)$, which exhibit in general a maximum around $\nu = 1$.
2. the second step was to correlate, for each discrete value of the imensionless frequency ν_k, the corresponding amplifications $A_i(\nu_k)$ with the site velocity $V_{Sz,i.}$ The rationale behind this correlation is simply that the lower V_{Sz}, the larger should be the amplification at the fundamental frequency. This is done by a least-square fitting of the following, NGA-like functional form

$$\log(A_i(\nu_k)) = a_k + b_k \log(V_{Sz,i})$$

or, in other terms,

$$A_i(\nu_k) = (V_{ref,k}/V_{Sz,i})^{\alpha_k}$$

Such a procedure has been performed for each of the four parameters V_{Sz}, with $z = 5$, 10, 20 and 30 m, and for both the original $BHRSR_{raw}$ values, and the depth-impedance corrected $BHRSR_{cn}$ ratios. A similar correlation has been looked for also with the fundamental frequency, having in mind that f_0 might be a proxy to the soil softness in a way similar to V_{S30}. Five different such "SAPE" (Site Amplification Prediction Equations) based on (V_{S5}, f_0), (V_{S10}, f_0), (V_{S20}, f_0), (V_{S30}, f_0) or f_0 alone, were obtained, an example of which is illustrated in Fig. 5.5 for the couple (V_{S30}, f_0).

The quality of such correlations is quantified through the resulting "misfit" between the actually measured amplification factors and the predicted ones. As displayed in Fig. 5.5b and Table 5.1, the main variance reduction is coming (a) from the depth-impedance correction and (b) from the transformation to dimensionless frequency. Once these steps are carried out, the best explanations of the amplitude variations are associated with the parameter couple (V_{S30}, f_0); however, very shallow velocities such as V_{S05} and V_{S10} also provide a non-negligible variance reduction. It is worth also to notice that, amongst the single parameter correlations, the best variance reduction is not obtained with the routinely used V_{S30} parameter, but with the f_0 parameter: the fundamental frequency thus appears once more as the key parameter, and should be preferred to an impedance index. Beyond their possible use and/or further testing in the derivation of ground motion prediction equations, these results could prove very valuable and easy to use for the next generation of building codes.

Table 5.1 Standard deviation and misfits resulting from the correlation between amplification functions and various site parameters

Parameters	Non corrected surface-downhole response spectra ratios: $\mathrm{BHRSR_{raw}}$	Depth-impedance corrected surface-downhole response spectra ratios: $\mathrm{BHRSR_{cn}}$
Initial standard deviation	0.268	0.202
V_{S30} only	0.255	0.174
V_{S20} only	0.257	0.177
V_{S10} only	0.260	0.184
V_{S05} only	0.264	0.190
f_0 only	0.254	0.159
(V_{S30}, f_0)	0.255	0.158
(V_{S20}, f_0)	0.255	0.159
(V_{S10}, f_0)	0.254	0.164
(V_{S5}, f_0)	0.255	0.168

The standard deviation and misfits are computed from the $\log_{10}$ values of observed and computed amplifications, and averaged over the whole frequency range from 0.25 to 20 Hz. For more details see Cadet et al. (2010c).

5.5 Conclusions

The outcomes of these series of investigations can be summarized briefly as follows:

- Non-invasive, surface wave methods do provide a reliable, lower cost alternative to existing and widely accepted borehole techniques. This is especially true for soft and intermediate stiffness sedimentary sites, which bear a particular importance since they favor higher amplifications.
- In particular, in view of simple site characterization, surface-wave techniques do provide reliable estimates of the time-averaged velocities V_{Sz}. In that aim, it has been shown that the inversion step may not be mandatory, and that EC8-type site classes could be derived with an acceptable accuracy directly from dispersion curves in the (velocity/wavelength) plane.
- However, when the target is the velocity profile $V_S(z)$ in view of forward computations of site amplification, surface wave-techniques can provide only smoothed estimates of $V_S(z)$, as they definitely cannot resolve thin layers. They nevertheless offer the non-negligible capacity to investigate large depth (up to several hundred meters) for very thick sedimentary deposits, and could then be viewed as a useful complement to (shallow) borehole measurements.
- When combined with the analysis of comprehensive, high quality strong motion data sets, these techniques pave the way for a simple two-parameter site classification, that performs significantly better than the classical one based on V_{S30} in terms of prediction of site amplification. The main improvements are that it relies on parameters which are easily available with simple, non-invasive, passive or active survey techniques, and that these parameters provide a more satisfactory link to the physics of site amplification, at east in the 1D case.

The initial goal of the NERIES research activity was the development of a reliable, low cost characterization of strong motion sites in Europe. It turns out however that these results can be extended to site characterization required by the majority of building codes in relation with the seismic design of constructions, and an improved estimation of the associated site amplification factors, with special emphasis on microzonation studies.

However, it must also be clearly emphasized that such *low-cost* tools should not be associated with *low-expertise* analysis. On the contrary, the acquisition, processing and interpretation of ambient vibration measurements should not yet be viewed as a routine elementary practice, and do require a rather high level of expertise. One of the key goals of the geopsy software tools, the associated on-line documentation and training courses, and all SESAME and NERIES reports, has definitely been to help the user in building his own expertise, and sharing his experience with a broad community. We hope the availability of open-source, fully understood software tools will progressively contribute to disseminate and generalize the use of non-invasive techniques, as a cost-effective complement and/or sometimes a substitute to the well-established borehole techniques.

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