UNCERTAINTIES ON VS PROFILES FOR SITE RESPONSE AT A VERTICAL STRONG MOTION ARRAY

Konstantia MAKRA¹, Dimitrios RAPTAKIS²

ABSTRACT

We present a study of various shear wave velocity, Vs, profiles at a test-site where a deep downhole array operates. For this, we benefit from the availability of 62 Vs models derived from seismic interferometry, stress–strain analysis and annealing simulation, based on earthquake data, conventional seismic prospecting (surface wave inversion, CrossHole and DownHole tests), and seismic noise array measurements. The estimate of Vs models differs depending on the technique used. Their disparity, albeit small, becomes significant at certain depths and is associated with the existence of strong vertical discontinuities, introducing an uncertainty on the interface definition between the main formations. Results from Quarter WaveLength and dispersion curves based on these profiles, show an analogous uncertainty, which should be treated with caution when engineering applications are involved.

Keywords: interferometry; accelerograph downhole array, Vs models, quarter wavelength, phase velocity dispersion curves

1. INTRODUCTION

Shear wave velocity (Vs) is deemed the most important parameter in earthquake engineering and engineering seismology studies. Its knowledge is useful for site effect estimations (e.g. Borcherdt, 1970; Aki, 1988; Bard, 1994; Chávez-García, 2011), seismic hazard assessment and Ground Motion Prediction Equations (e.g. Boore, 2004; Abrahamson et al., 2008; Douglas et al., 2009), microzonation and other site specific studies (i.e. liquefaction, soil–foundation–structure interaction, etc.). On the other hand, the exploration of Vs velocity is a rather non-straightforward task due to its non-unique evaluation from different techniques and the nature of the demands of the anticipated study (Raptakis et al., 1996; Brown et al., 2002; Stephenson et al., 2005; Asten and Boore, 2005; Kuo et al., 2009; Raptakis, 2012; 2013; Raptakis and Makra, 2015; Garofalo et al., 2016). If there are many Vs profiles at a site, usually, either one of them is selected to be finally used or an average is simply computed; but this does not provide an answer to the question, why different Vs estimates exist at a site. Thus, it would be more interesting to understand the reasons for such a disparity and then to quantitatively evaluate it. In this context, the usefulness of single indexes (e.g. Vs30, Vs100, Vs(z1.0, z2.5, T0, etc.) to represent site effects in many hazard assessment demands (e.g. seismic norms, GMPEs, etc.) may be debatable.

In addition to the above, those single values is attempted to be correlated with parameters inferring consequences triggered by earthquakes, such as T0 period, or other more sophisticated parameters such as the delay time of S-wave propagation at shallow sediments and the frequency content including resonances. To this end, an alternative approach based on dispersion curves of phase velocity with wavelength or frequency as free parameter, is proposed and commented based on its relative

¹ Senior Researcher, Institute of Engineering Seismology and Earthquake Engineering EPPO-ITSAK, Thessaloniki, Greece, makra@itsak.gr
² Professor, Aristotle University of Thessaloniki, Department of Civil Engineering, Thessaloniki, Greece, raptakis@auth.gr
advantages. Thus, 62 estimated Vs profiles are presented in brief following our previous work (Raptakis and Makra, 2015), that were derived from a set of all usual non-invasive and invasive techniques, at one site, at the center of a rather shallow basin known as Mygdonian basin or EUROSEISTEST site (Raptakis et al., 2000; Raptakis et al., 2005; Manakou et al., 2010; Chávez-García et al., 2014; Hannemann et al., 2014). Their differences are reviewed and averaged profiles based on different techniques are proposed and compared to each other as well as to a combined reference Vs model until intact bedrock (Vs~3200 m/s) at a depth of about 1575 m, as well. We found that uncertainties in Vs profiling are mostly due to inadequacy of wavelengths to track successive layers with certain Vs contrast. Then, emphasis is given in the ensuing to a comparative study between different soil models performed based on two different tools for evaluating the induced uncertainty; namely, the Quarter WaveLength (QWL) amplification curves (Joyner et al., 1981; Brown et al., 2002), and the phase velocity dispersion curves of the fundamental mode of the Rayleigh wave as a function of frequency and/or wavelength (Raptakis, 2013), as alternative approaches to evaluate the disparity of different models.

2. Vs PROFILES AT TST SITE

The site under study is situated at the center of EUROSEISTEST (Mygdonian) basin. A vast amount of geotechnical and geophysical surveys has been deployed at this test site during the last 25 years including seismic prospecting methods, microtremor measurements, and in-situ and laboratory geotechnical tests, leading to a 2D (Raptakis et al., 2000; Raptakis et al., 2005) and a 3D model structure (Manakou et al., 2010). Specifically, at its center (TST site) where a deep 3-component accelerometer down-hole array has been installed, all measurements and analyses are gathered to build the most precise and accurate possible soil model. This vertical array (www.dbseis.civil.auth.gr, Pitilakis et al., 2013) consists of 6 accelerometers; at surface, 18.7, 40.0, 73.1, 136.0 and 196.0 m depths; the last located at sediments–bedrock interface with common trigger, absolute time as well as orientation control of the horizontal components. The analyses of DH earthquake recordings result to shear wave velocity profiles of the sedimentary formations and are presented herein together with Vs profiles from conventional seismic prospecting and array noise measurements.

2.1 Seismic interferometry technique (CC)

Recordings from 8 earthquakes at the vertical array were used to determine the Vs velocity distribution with depth (Figure 1a) using seismic interferometry on recorded ground motion. Details on the processing of the raw data and the computations are already described in Raptakis and Makra (2015). The results show that, phase velocity derived from the pronounced very onset first S-wave arrival, are quite stable with small standard deviation (less than 8%) despite that data used come from earthquakes with different azimuths, epicentral distances and focal depths, parameters that may affect the vertical near surface propagation of body waves. The small scatter is related with the use of a single phase of the signals. The similarity of Vs velocities between horizontal components does not suggest any significant anisotropy effect, thus an average of both components can be considered representative at the site, for this method.

2.2 Stress–strain ($\tau$–$\gamma$) analysis (SS)

Six earthquake recordings at the vertical array used to define the stiffness of sediments in an alternative way using stress–strain ($\tau$–$\gamma$) analysis (Zeghal et al., 1995; Elgamal et al., 2005). Details can be found in Raptakis and Makra (2015). Figure 1b shows the Vs velocity distribution with depth (from 9 to 166 m) for both horizontal components together with their mean value and ± 1 std. In both components, Vs values are very similar and quite stable for all soil formations with a small exception for the layers between 55.5 m and 104.5 m depths, with less than about 12% average standard deviation. At greater depths, the scatter is quite large (20–35%) related with the fact that stations are positioned at large intervals (of about 60 m). This does not allow computing coherent stress and strain histories, since a) up- and down-going body waves are superposed with laterally propagated surface
waves from “basin edge” diffractions (Raptakis et al., 2000; Chávez-García et al., 2000), and b) contamination of inverted P- and S-phases at the intermediate interfaces, biases both the amplitude and frequency content of the first period of S-wave with direct consequence on the shape of stress–strain ellipses. Finally, mean Vs models from both horizontal components are almost identical, suggesting a rather reliable estimation of an overall mean Vs profile (Figure 1b), which is very alike with that of seismic interferometry.

2.3 Adaptive Simulated Annealing Algorithm (ASA)

Another way to analyze data from the vertical array is to use algorithms based on simulated annealing (SA) such as general Monte Carlo approximation methods that allow optimizing problems when a desired global minimum is hidden among many local minima (see details in Chávez-García and Raptakis, 2008). Velocities $V_p$ and especially $V_s$ (at the topmost layers and for frequencies smaller than 5 Hz, in this case) are used in the inversion scheme and they are fixed when synthetic and empirical spectral ratios of 8 earthquakes match. Their good agreement for both components, leads to the Vs profile of Figure 1c. Disparities with previous models, in both velocities and depths, are expected since the thickness of soil layers considered in ASA method, was a priori determined from the 2D soil model of Raptakis et al. (2000).

![Figure 1. a) Vs profiles using seismic interferometry (CC) analysis on radial (red lines) and transverse (blue lines) components of recorded ground motion with their mean value $CC_R$ or $CC_T$ and their mean value ± 1 std (dashed lines) and overall mean Vs ± 1 std profile (black lines), b) the same using stress-strain analysis (SS) and c) ASA model](image)

2.4 Conventional seismic prospecting techniques (CONV)

Since 1993, many different groups of reversed seismic profiles for seismic prospecting have been deployed for short S-wave refraction tests including Love wave inversion analysis, and intermediate and long P-wave refraction tests for Rayleigh wave inversion. This sample of data presents a variety of Vs profiles. All these surface measurements together with CrossHole (CH) and DownHole (DH) tests are performed in a limited area (of about 0.25 km$^2$) around TST site and their analysis led to a total of 26 Vs profiles (Figure 2).

Field measurements of different lengths, geophone spacings and offsets are performed to achieve good resolution Vs profiles at depths from top to 10 – 40 m (Figure 2a), and to 140 – 190 m; i.e. from top to
bedrock (Figure 2b). A detailed and thorough presentation could be found in Raptakis and Makra (2015). Finally, an average 200 m Vs model was built up considering the ability of each analysis to provide detailed layering with respect to penetration depth (Figure 2c). This combined model shows a successive increase of Vs values with depth, from about 100 m/s to 1200 m/s, and considerable vertical Vs changes at 2, 4, 10, 20, 40, 60, 140 and 180 m depths with a corresponding increase of the order of 40, 17, 24, 31, 27, 15, and 26%. At all depths, the standard deviation is less than 15% except specific horizons at 15–20 m, 50–60 m, 120–140 m, and 155–190 m depth of higher scatter (18–28%).

![Figure 2](image)

**Figure 2.** a) Near surface Vs profiles (14 in total) where REF stands for S wave refraction analysis, CH & DH for cross-hole and down-hole tests and the rest from surface wave inversion analysis (SWI), grouped in 3 sets (SA, SB, SC) according to their maximum penetration depth (10, 16 and 40 m respectively) for which an average model was computed and presented in panel c) with blue, red and green lines. b) Vs profiles (12 in total) from surface wave inversion analysis (SWI) of Rayleigh wave dispersion data grouped in 2 sets: inverted Vs profiles on dispersion data from S1L_S seismic section (with 10 m offset) and inverted Vs profiles on dispersion data from S1L_L seismic section (with 280 m offset), (c) Composite Vs profile – CONV (mean values & mean ± 1std noted with black solid and dotted lines respectively) together with average SA, SB and SC (short) Vs models presented in panel a) and average L (purple line) of all long Vs models presented in panel b).

### 2.5 Ambient noise array measurements (ANM)

In addition to the above, array microtremor measurements (ANM) were obtained with various scaling of circular arrays in different seasons of the year (Kudo et al., 2002; Apostolidis, 2002) and analyzed with Spatial Auto-Correlation coefficient (SPAC) technique (Aki, 1957; Okada, 1998). Ambient noise recordings of two sets from different circular arrays – a small of 4 broadband instruments and a large of 7 ones – were analyzed to obtain experimental dispersion curves and two different approaches to invert them into Vs profiles (Figure 3). The early obtained Vs profiles (GPA and JHK), except one, reach 1575 m of depth, where a Vs of 3200 m/s, that of the intact bedrock, is found and are further supplemented with five new analyses (Raptakis and Makra, 2015). All these Vs models show significant stability in their resolution until 165 m depth, with an average disparity less than 10%, except for the top 10 m and between 110 and 120 m where the observed disparity is slightly larger than 20%. Scatter of similar order is also observed at all depths for the rest of the profile until bedrock with an exception close to 185 m (± 20 m) depth, where it gets the maximum value (~50%). At this depth, a large impedance contrast between sediments and weathered bedrock is present. An average Vs profile (Figure 3) is finally adopted, knowing that the large array spacings does not allow a detail Vs distribution at the very surficial layers (< 10–20 m). Vs variations with depth are larger than 20% at 10, 30, 165, 190, and 1575 m.
3. COMPARISONS BETWEEN Vs PROFILES AND UNCERTAINTIES

Upon availability of 62 Vs profiles as a result of the implementation of different methods in various datasets, we take the opportunity to briefly present, in this section, a discussion of strengths and weaknesses of each approach, comparing mean Vs profiles assembled in five groups with respect to the applied method (Figure 4a). This comparison gives the opportunity to evaluate the differences between Vs exploration methods and to reveal the sources of the observed scatter. It is worth noticing that the observed differences between the mean Vs models cannot be accounted for as a measure of goodness of one technique relative to the others, but rather as an index of the differences in principals and assumptions of each method to explore the subsoil structure; i.e., the efficiency of the applied methods to detect spatial in-homogeneity of soils (layering stiffness gradient and inclination, degree of heterogeneity, and Vs contrasts).

In this sense, the mean CC and SS models, which are based on the analysis of earthquake recordings, have an inherent limitation to discern layers of Vs velocities with thickness smaller than those fixed at inter-station distances as well as ASA profile which is built based on fixed thickness of the sublayers at TST. Moreover, regarding conventional techniques (CONV), the inefficiency of the active source energy to penetrate deep soil horizons in combination with soil heterogeneity affects the depth resolution. Layering resolution of surficial layers is related to the consistency of detected wavelengths with array measurements configuration. Finally, techniques based on ambient noise recordings at wide spread arrays, although large resolution depths were obtained, fail to explore with high discreteness top soil layers due to inconsistency between small layer thickness and large detected wavelength.

The main issue that arise between models of the same group refers to the uncertainty of the horizons depths, which is expressed with a significant scatter (> 20%) with respect to the averaged per group Vs profile (Figure 4b). This scatter mostly appears at deep vertical discontinuities (> 100 m), where very stiff formations with large impedance contrast do not allow the penetration of sufficient source energy; frequently the latter is trapped within overlying layers. In this regard, techniques based on a single

Figure 3. Vs profiles (7 in total) from SPAC method, together with their mean ± 1 std, a) top to 200 m sediments, b) from the top to 1600 m depth.
phase of the recording e.g. the very onset S-wave, provide models without significant scatter (interferometry analysis CC, SH-refraction, DH and CH tests). The scatter in both Vs velocities and interface depths becomes significant, when more sophisticated techniques were applied; using certain time-windows of the recordings, as for example an S-wave complete period (τ–γ ellipses), surface waves (dispersion curves) and transfer functions (ASA).

Moreover, a mean representative Vs model of all 5 models is proposed as reference (REF). This model balances all available information in such way to take into consideration imperfections of results. An example of this refers to Vs velocities within the first 10 m. Overall mean Vs velocity at the surface layer is of about 150 m/s, which is larger than that provided (Vs ~ 95 m/s) from the short but more accurate seismic profiles according to thickness of layers and wavelength relationship. Thus, we decided to assign to the REF model, the lower value for layers within the first 10 m, rejecting those of low sensitivity methods. Another attribute of the REF model refers to the increase (of an order 10–20%) of the mean Vs velocity at 10, 20, 40, 135, 165, 180, 190, and ~1575 m depths. No significant or unique Vs contrast is observed, a fact that indicates a very heterogeneous stratigraphy of soil mix formations that constrains well with geotechnical description and N_SPT values as well as with V_p velocities from long P-wave refraction tests (Raptakis et al., 2000).

Model REF presents an average quasi-constant scatter (10–20%) with respect to mean Vs profile of each group, at all depths down to ~195 m (weathered bedrock). An increase of scatter (> 15–20%) is observed at depths that are associated with an identified increase of Vs velocity at 10 and 20 m, 30 and 50 m, 60 and 80 m, and 165 m and between 185 and 195 m e.g. intermediate sediments interfaces. Certainly, the fact that scatter is higher close to interfaces, shows the relative uncertainty of their exact depth. On the other hand, these indications lead us to identify that scatter has at least a remarkable physical (or epistemic) cause related with alterations of geological formations. Both scatter and Vs variation between models and layers, indicate the disparity between the techniques used to investigate one of the most (if not the most) important parameter in site response analyses. This overall disparity
is 17% for CC, 12% for SS, 21% for ASA, 8% for CONV and 12% for ANM profile (Figure 4c). Thus, a maximum of 20% disparity could be safely adopted as a realistic bound of the shear wave velocity distribution with depth (Stephenson et al., 2005).

4. COMPARISONS IN FREQUENCY DOMAIN AND UNCERTAINTIES

In this section, we extend the comparative study between five models and REF, but in a different way. We do not explicitly compare Vs velocities with depth as previously, but velocities as a function of frequency provided either prior or after the realization of the Vs profiles. This approach is motivated from the ongoing discussion on how to consider site effects in Ground Motion Prediction Equations (GMPEs), as for example, in a more sophisticated way, rather than a single value such as VS30, which is nothing more but only a point in the quarter-wavelength (QWL) representation.

4.1 QWL analysis (site response)

Quarter WaveLength (QWL) technique was introduced by Joyner et al. (1981) and widely implemented by Boore (2003), for the evaluation of site amplification as a function of frequency, according to the formula $A(f) = \left(\frac{\rho_B V_{SB}}{\rho_A V_{SA}}\right)^{1/2}$, where $\rho_B$ and $V_{SB}$ the density and the shear wave velocity of the reference layer of the Vs profile. In this study, the QWL approach is applied for the quantitative comparison between models with respect to the REF one, according to the relation $A_{c_{\text{model}}}(f) / A_{ref_{\text{model}}}(f) = \left(\frac{V_{SAVE_{c_{\text{model}}}}}{V_{SAVE_{\text{ref_{model}}}}}\right)^{1/2}$, since: i) amplification functions are of much simpler shape than classical transfer functions, ii) the quantitative comparison of many different Vs profiles is easier, iii) its application yields good estimates of high frequency amplification without the constraint of knowing the deep profile, and iv) it is based on the total travel time of the propagated S-wave and smoothed slowness instead of measured Vs in the field.

Figure 5a shows QWL amplification as a function of frequency for REF and five mean Vs profiles of Figure 4a. All Vs models were extended at 1600 m depth adding Vs velocities provided from the ANM model. For simplicity reasons, attenuation or $\kappa$ factor was not considered, and mass densities were the same for all profiles. Amplification factor for all models, despite their differences, continuously increases (~3 and ~4.25-6.25) from 0.5 to 10 Hz, indicating that the whole profile contributes to site effects and not only the upper layers (e.g. the top 30 m).

![Figure 5a](image_url)

Figure 5. Amplifications of each mean Vs model and REF one (left) and relative amplification between averaged models with respect to the reference one (right)

Consequently, knowing the discrepancies between Vs models with respect to REF one, we quantitatively evaluate their differences in terms of site response (Figure 5b). CC and ANM relative amplification curves mostly underestimate amplification with respect to REF model of an average percentage for all frequencies of 24% and 16%, respectively. The smallest differences are observed for
SS and CONV models (0.2 and 4.5%, respectively), while ASA presents the larger disparity at frequencies up to 2 Hz. These differences in amplification (up to 16%, except that for CC) is quite analogous but much lower with respect to the differences in $V_s$ values, as well as with those measured in the uppermost layers as expressed by the $V_{s30}$ parameter; 21% for CC, 30% for SS, 21% for ANM and 11% for ASA, 5% for CONV. $V_{s30}$ disparity in the amplification of the order 5-30% is sufficient to be cautious against which model could be used to represent soil conditions at the site.

4.2 Dispersion curves (“direct problem”)

In a vertically heterogeneous medium, surface waves involve in their propagation different layers and consequently the Rayleigh wave dispersion curve of phase velocity will be related to a combination of their mechanical properties as a function of frequencies and wavelengths as well. In this context, frequency is related to the resonance of the subsoil structure and wavelength is associated with the effective depth. Hence, we decided to use dispersion data instead of $V_s$ models. An important reason of using dispersion curves is, the possibility to quantitatively compare results of different techniques directly (such as SWI, SASW, SPAC, ReMi, F-K, etc.) and indirectly (for DownHole, CrossHole, SH-refraction tests, as well as those from interferometry CC and stress-strain analyses SS), for which dispersion curve can be theoretically obtained, from the available $V_s$ models. Certainly, frequency content of the dispersion data cannot directly correspond to that of QWL curves, given that frequencies together with velocities (phase or group) determine propagation wavelengths ($\lambda$) and therefore the depth ($z$) limits, for which the obtained $V_s$ model could be acceptable (e.g. $\lambda/3 < z < \lambda/2$, according to the complexity of soil conditions).

Phase velocity curves are selected (instead of group velocity) because i) $V_s$ models, such as CC one, correspond to the velocity of the first S-wave, namely a phase velocity, that can be easily deduced by S-wave time lags from borehole earthquake recordings, ii) phase velocity dispersion curve is almost a continuous monotonic function of frequency with simpler shape comparing to that of group velocity and iii) many geophysical field techniques make use of surface waves phase velocity curve. Consequently, with these assumptions in mind, Figure 6a shows theoretical dispersion curves of phase velocity of the fundamental mode of Rayleigh waves with respect to frequency solving the “direct problem” with proper codes developed by (Herrmann, 1987), for all five averaged $V_s$ models and model REF, extended down to 1600m depth, and compared, at the same time, with observed dispersion data from ambient noise (ANM) analysis and one example of dispersion data from the group CONV. At this point, it is worth mentioning that dispersion curves might be considered to be free of subjective and debatable inversion processes. Furthermore, Figure 6b shows the same dispersion curves but as a function of wavelength, implying depth of the soil profile.

![Dispersion Curves](image)

**Figure 6.** a) Theoretical dispersion curves (lines with symbols), for all mean $V_s$ models CC, SS, ASA, CONV, ANM, and REF, with two examples of experimental curves (symbols) b) The same dispersion curves but as a function of wavelength

Taking advantage of the good agreement between theoretical and experimental curves, we emphasize
on the correlation of theoretical ones with the corresponding QWL curves. It is observed that all curves are close to each other, for a large frequency band, with the exception of ASA one. Following the same concept as for Vs models (Figure 4c), the difference between dispersion curves of each model and that of REF was computed in terms of the same misfit function (%) as previously. In this case, the wavelength instead of depth was used as free parameter. Figure 7a shows a rather similar order of uncertainty observed for all dispersion curves (averaging 22-34%). Indeed, this disparity is distributed almost at all wavelengths that is to say for all related depths and not only for those of deeper and the thicker formations. Once the relation between wavelength λ and depth z is established, the square root of the ratio of inverted dispersion (e.g. slowness) curves $\sqrt{(MOD^1/REF^1)}$ for each model is computed (following Raptakis, 2013) similarly to the hypothesis of QWL (comparative amplification ratio). Figure 7b shows almost a similar picture not only with phase velocities and wavelengths diagrams, but also with Figure 5b that compares relative amplification for QWL results. However, in this case the observed scatter, using directly dispersion curves instead of amplification curves based on Vs profiles, seems to be much lower (~1-11%, except that of ASA curve) at all frequencies with respect to QWL. This is a promising outcome if extrapolated to field measurements, with reference to the direct use of experimental dispersion curves, omitting the complexities and the uncertainties of the inversion process.

Figure 7. a) The percentage (%) misfit or “error” function on phase velocity disparity (between CC, SS, ASA, CONV, ANM models relative to REF) Vs wavelength showing large values, similarly to the Vs differences with the depth similar to Figure 4. b) Square root of the ratio of inverted dispersion (slowness) curves of each model with REF, likewise to relative QWL amplification of Figure 5b.

5. CONCLUSIONS

We have benefited from the investigation of 62 Vs profiles at a vertical strong motion array, derived from earthquake records, conventional seismic prospecting, and seismic noise array measurements. Five groups of models provided from 9 different invasive and non-invasive methods lead to averaged Vs profiles, to compare them according to each technique. The investigation of a Vs profile is not a straightforward task, as all Vs profiles differ. However, we cannot discern which one is correct and which is not. We believe that all profiles represent reliable models on the base of the hypotheses and theory of each technique. Thus, the use of many techniques introduces certain uncertainty for the most standard parameter for site effects evaluation.

The observed scatter of models for each group is an indication of the uncertainty of the estimate. In general, less scatter is observed for models based on the analysis of a single phase (S-wave first arrival). In contrast, this scatter becomes significant when the analysis concerns more than one single
phase, such as complete periods of S-wave (SS model) or surface waves propagated in different modes (models in CONV). However, the techniques based on S-wave first picking have disadvantages (average between fixed receivers, e.g. CC, or small penetration depth, e.g. S-refraction, CH, DH, etc.), with respect to those with which a thorough analysis of surface wave results to as deep as possible profiles with layering thickness acting as a free parameter. The average of the gathered models with their percentage standard deviation for each group show that the last is larger at depths of the layering interfaces, with an at least 20% increase of Vs velocity. This is a consequence of wavelengths weakness of the trapped waves to penetrate the successive deeper layers. Moreover, the mean models in comparison with REF albeit is by average less than 20%, this becomes significant at depths associated with the strong vertical discontinuities, thus introducing an uncertainty on the interface definition between the main formations. Vs for all depths, mostly for the upper 30 m, present an average scatter of 18% reaching a maximum of 30% introducing ambiguity for its standard usage. Concluding, in cases where several techniques can be applied to obtain the Vs model at a site, the user instead of computing an average, considering data in hand, must select on the basis of the specific aims of the study, taking into account advantages and disadvantages of exploration tools, simplicity and robustness of the models vs more sophisticated ones in which layer thickness is a free formed parameter.

Comparisons between models become better when other approaches not exclusively based on Vs models are involved. QWL technique used for site amplification shows that the disparity between time-averaged shear wave velocity models is quite less (average ~10%) than the Vs models (for all depths and mainly for the first 30m). However, original data as those of travel-times picking first S-wave could be gained only from smaller precision techniques (e.g. DH and S-refraction tests), and for small penetration depths (e.g. for some decades of meters) as well. On the other hand, similar or less order of uncertainty is observed using dispersion curves of phase velocity of Rayleigh waves (fundamental mode). This approach concentrates more advantages than the others, since dispersion data could be immediately detected with field measurements (seismic noise) and for large effective depths (e.g. several hundreds of meters); overcoming the criticism for the subjective and debatable Vs inversion processing. Converting frequencies into wavelengths provides useful information at the same time for depths of interest too. In addition to the above, more general conclusions could be drawn. First, if more data (e.g. Vs models) are added, the uncertainty (regarding Vs velocities, layering interfaces, etc.) does not decrease, and it is observed for all sedimentary formations at all depths and not only for deeper and thicker formations, as it is widely thought. The situation is significantly improved by using continuous functions related to frequency or wavelength provided from phase velocity dispersion curves, concentrating more advantages than QWL. However, the problem remains. Finally, taking into account that uncertainties are mainly due to field conditions concerning the physics of the tools used, a posteriori statistical improvements cannot significantly correct the problem.

6. REFERENCES


