Vs Measurements through Dispersive Wave Methods in the Urban Environment of Porto (North Portugal)

R. M. Moura & F. Noronha
CGUP, University of Porto, Faculty of Sciences, Portugal

R. Umaraliev
Humanitarian and Pedagogical Institute, University of Osh, Kyrgyzstan

F. Almeida
Departamento de Geociências da Universidade de Aveiro, Aveiro, Portugal

G. dal Moro
Eliosoft, Palmanova (UD), Italy

SUMMARY:
The measurement of shear wave velocity (*Vs*) is an established approach in contributing to earthquake site response. In situ dispersive wave measurements are one of the ways of determining *Vs* to a certain depth. Rayleigh type measurements have had a significant development in the past two decades. Since Spectral Analysis of Surface Waves measurements appeared, in the late 80s and early 90s, other approaches have developed. The later Multichannel Analysis of Surface Waves method (MASW), that took advantage of the engineering seismograph and the increasing number software routines that became available, greatly enhanced the confidence of this type of in situ results towards assessing the shear wave velocity profile of the near surface.
Currently, in terms of source signal used to stimulate the ground in the multichannel approach, we have two categories: the passive type, by use of environmental noise and the active type, which usually make use of a hammer, a vibrator or even a small explosive charge. More recently, in terms of sensors, horizontal geophones have been added as an option to the more common vertical geophones and thus being able to measure Love waves. In terms of processing the most recent development has been the possibility of joint inversion of data sets of different types (Rayleigh+Love, Rayleigh+HVSR, Rayleigh+Refraction).
Since some of most important earthquake site response measurements have to be performed in urban environments this can pose a problem to the in situ measurements due to the lower signal to noise ratio. Thus we aim to show some case study results of dispersive wave tests, made in the urban environment of the city Porto in Northern Portugal, with the objective of contributing towards a microzoning GIS map that we are currently engaged in improving. Porto is set in a crystalline environment with a rock mass that is variably weathered thus our test results will be compared with the geotechnical map of Porto.

Keywords: dispersive waves, MASW, microzoning, (Vs) shearwave velocity

1. INTRODUCTION

The increasing concern regarding the current levels of heritage preservation due to natural risks motivated the appearance of the “Operação Quadro Regional (OQR) - NOÉ – Heritage and Prevention due to Natural Risks” within the scope of the European Community initiative INTERREG III C. The “OQR NOÉ”, led by the region of Provence-Alps-Quote d' Azur (PACA, France), involved the region of North Portugal (CCDR-N), the regions of Molise and Sicily (Italy) and the region East Atica (Greece) and aimed at the development of preventive measures to save cultural heritage due to the natural hazards.

In this scope, it was intended to carry out an evaluation of current existing practices by means of a strategy of interregional cooperation between the NOÉ partners and to develop specific field actions together with strategies of prevention, alert and intervention suitable to the heritage, public awareness and responsibility of the local agents and decision makers, implementation of trans-regional experiences, development of new technologies, euro-Mediterranean cooperation and also to support each other in the innovative operations. It is in this way that the subproject GEORISK appeared, that joined, in an interregional cooperation, the City council Porto (CMP), the Bureau of Recherches Géologiques et Minières (BRGM), the Department of Geology of the Faculty of Sciences of the University Porto (DGFCUP) and the Portuguese Institute for Cultural and Architectural Heritage (IPPAR), now called Institute of Management Architectural and Archaeological Heritage (IGESPAR). The city of Porto is located in the Northwest of Portugal (Figure 1). The "Seismic Hazard Map of Porto" (Moura *et al*, 2009) consisted the starting point and was obtained from a previously available set of information under the form of a geotechnical cartography, topographical elements and some geophysical measurements performed on the main geotechnical formations.

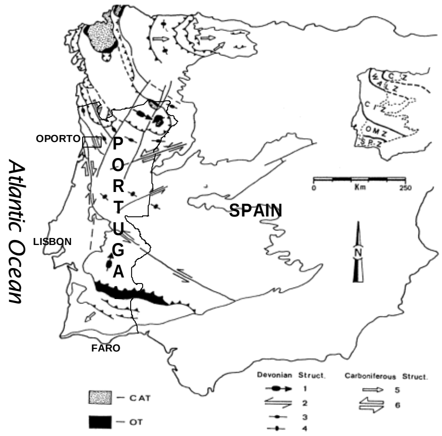

Figure 1. The Geographical location of Porto. (Adapted from Almeida and Begonha, 2008)

The Geotechnical Map of Porto (Câmara Municipal do Porto, 2003), figure 2, was updated with new more recently compiled data and also with the aid of some new field observations.
After these corrections were made the geotechnical rock and soil formations can be translated in terms of their shear modulus using the formula:

$$G_0 = Vs^2 * \rho \quad (1)$$

In the formula *Vs* corresponds to the velocity of shear waves and ρ the corresponding average density. The shear wave velocity values (*Vs*) were derived from seismic dispersive wave testing using both vertical and horizontal geophones. The shear wave velocity values express a direct relation with mechanical properties and thus are very influential in terms of the local site response when seismic energy is received and can thus constitute an amplification factor (Eurocode 8).

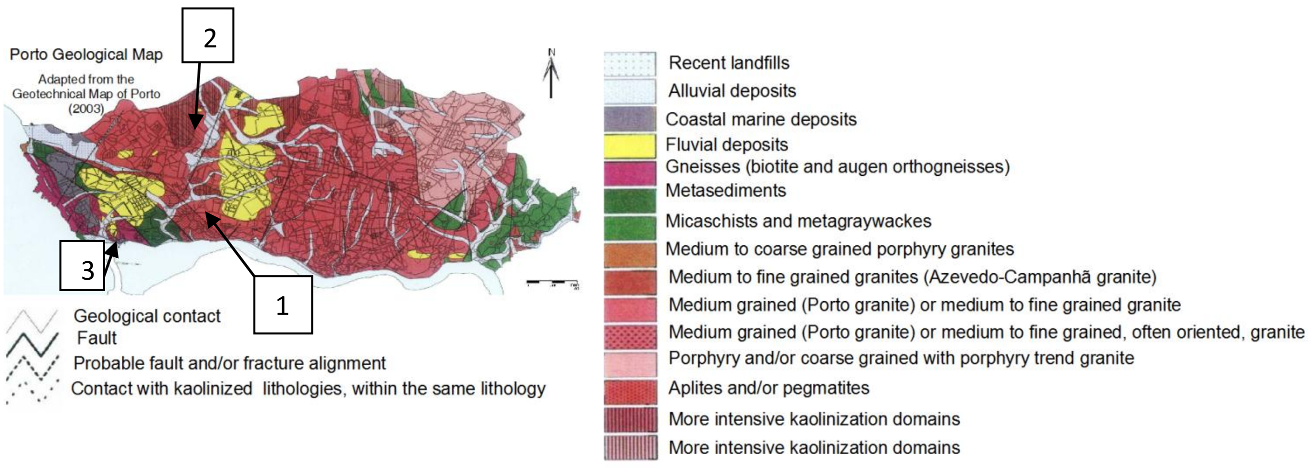

Figure 2. The Geotechnical Map of Porto along with the locations of three of the seismic dispersive surface wave tests. (Adapted from Almeida and Begonha, 2008)

We will thus focus in this work on presenting dispersive shear wave results in three distinct locations of the Porto Geotechnical map as well as some of the alternative ways of obtaining the resulting shear wave profile.

2. METHODOLOGY

The reasons that contribute towards such an interest are the increased consciousness and comprehension that the design of the structures response to dynamic forces exerted by earthquake, wind, vibrations, explosions, etc. This can be achieved by identifying the dynamic properties and hence by determining the shear wave velocity profile *Vs* of the sites by means of a properly studied methodology; Another reason is the need of a relatively simple technique, which can be sufficiently accurate and overcome some intrinsic drawbacks of other alternative direct geotechnical techniques that rely on sampling or destructive testing.

The local seismic classification of a site essentially consists of determining the category to which the site belongs on the basis of the main parameters which influence the site response to earthquakes or more generally to external dynamic forces. Currently there are several international codes, which classify the sites on the basis of their nature and their geotechnical characteristics, especially based on the vertical shear wave velocity profile.

The NEHRP (2006) (Table 1, right), Eurocode 8 (2004) (Table 1, left) or RPA regulations help to determine the seismic design force on the basis of the seismic zone to which the site belongs. The first classes (A or S1) corresponding to surface rock (see tables 1 and 2). When sites have type B (S2), C (S3), D (S4) or E geotechnical characteristics then the seismic motion at the bedrock generally is different from the seismic motion at the free surface, depending on the intensity and the frequency content of the seismic input, on the thickness and the geotechnical characteristics of the soil overlaying the bedrock. If a specific analysis of wave propagation is not performed at the site, then the spectral seismic acceleration at the free surface can be evaluated by means of a factor S and a spectral shape provided by the seismic code. For the other types of site the classification is defined by means of the equivalent vertical shear wave velocity, Vs^{30} (1), within the first significant 30m of the site in which *Vi* and *di* are respectively the vertical shear wave velocities and the thicknesses of the *i-th* layers of the soil over the bedrock (Vs^{30}, calculated as the traveltime ratio for shear waves to travel from 30m depth to the ground surface (1)).

The MASW method is a non-invasive investigation technique, through which the vertical profile of *Vs* can be obtained by measuring the propagation of the surface waves at several geophones or even accelerometers at the free surface of the site.

Generally the main contribution to the surface waves is given by the Rayleigh waves, which travel through the upper part of the site at a speed, which is correlated to the stiffness of the ground.

In a layered soil Rayleigh waves are dispersive, that is Rayleigh waves with different wave lengths travel with different velocities (both phase and group velocities) (Achenbach, 1999; Aki and Richards, 1980). Dispersion means that the apparent or effective phase (or group) velocity depends on the propagating frequency. This circumstance implies that high frequency waves with relatively short wave lengths contain information about the upper part of the site and low frequency waves, with longer wave lengths, provide information about the deeper layers of the site.

The dispersive wave methods can be applied as an active method, generally known as MASW, or as a passive method (Zywicki, 1999), generally known as passive MASW, ReMi or ESAC, or even as a combination of both active and passive.

Table 1. Ground types defined in EC8 (left) and site classification as per NEHRP (right)

Ground Type	Description of stratigraphic profile	Parameters V_s^{30} (m/s)	SPT	C_U (KPa)
A	Rock or other rock-like geological formation, including utmost 5 m of weaker material at the surface.	> 800		
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterized by a gradual increase of mechanical properties with depth.	360 – 800	> 50	> 250
C	Deep deposits of dense or medium dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.	180 – 360	15 - 50	70 - 250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with V_s^{30} values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with V_s^{30} > 800 m/s.			
S1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content	< 100 (indicative)		10 - 20
S2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S1			

NEHRP Site Class	Description	V_s^{30}
A	Hard rock	> 1500 m/s
B	Firm and hard rock	760 – 1500 m/s
C	Dense soil, soft rock	360 – 760 m/s
D	Stiff soil	180 – 360 m/s
E	Soft clays	< 180 m/s
F	Special sandy soils, eg. liquefiable soils, sensitive clays, organic soils, soft clays > 36 m thick	

$$V_s^{30} = \frac{30}{\sum_{i=1}^{N}\left(\frac{d_i}{v_i}\right)} \quad (2)$$

In the active method the surface wave is generated by a source located at a point on the free surface and then the wave motion is measured along a linear array of sensors. In the passive method the sensors and be located in arrays of different geometric shapes: linear, circular, triangle, square, L shape, and the source is represented by the environmental noise, whose direction is not known a priori. The active method generally allows the determination of an experimental apparent phase velocity (or dispersion curve) within the frequency range above 5Hz and up to 100Hz. Hence, depending on the stiffness of the site, the active method has the potential to provide information concerning the first 30m-35m in depth of the subsoil profile. The passive method generally allows to definition of an experimental apparent phase velocity (or dispersion curve) within the frequency range of 1Hz to 30Hz and hence the passive method generally is able to provide information about deeper layers, even below 50m and again depending on the stiffness of the site.

3. INTERPRETATION

The conventional way of obtaining results from the MASW method basically consists of three steps. In the first step (Figure 3a) the experimental apparent phase velocity spectra is determined from the multichannel shot record (Figure 3a). In the second step the numerical theoretical apparent phase velocity is calculated and can be compared with a picked dispersion curve (Figure 3b), In the last step the vertical shear wave velocity profiles can be modeled or searched for by properly modifying the thickness h, the shear (*Vs)* and compressional (*Vp)* wave velocities (alternatively to modifying *Vp* it is possible to modify the Poisson's parameter), the mass density of all the layers considered in the site model, until the optimal match between the experimental and the theoretical dispersion curves is achieved (Figure 4). During this last step the site model and hence the shear wave velocity profile can be determined by means of a trial and error or an automatic procedure, or a combination of both. Usually the number of layers, the Poisson's parameter and the mass density are assigned and successively the thickness and the shear wave velocity of the layers are modified. After the shear wave velocity profile has been determined, then the equivalent Vs^{30} (1) can be calculated and hence the seismic class of the soil can be established.

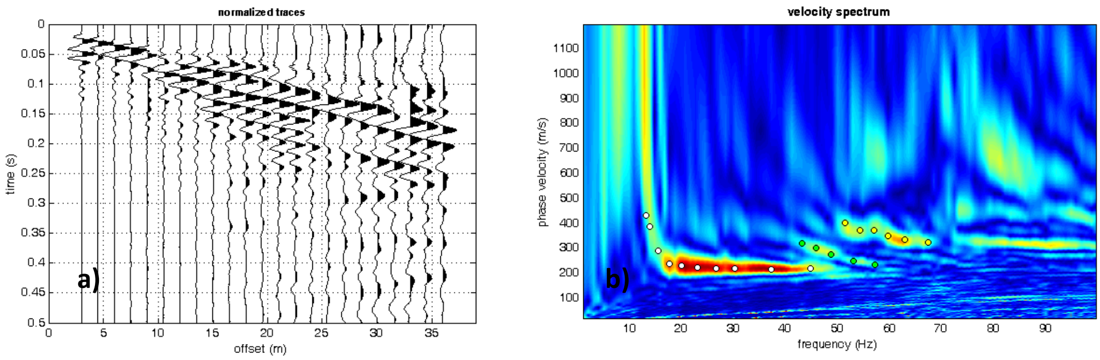

Figure 3. Multichannel shot record a) Frequency - Phase Velocity spectra with fundamental mode picking, and two additionally picked higher modes.

The ReMi (Refraction Microtremors) method, on the other hand is able to obtain information within the frequency range of 1Hz-30Hz, depending on the available environmental noise, hence it can give information about layers deeper than 30m and potentially down to 100m, as it is has been stated (Louie, 2001). Regarding this, the ReMi method is in some terms equivalent to the passive MASW. By combining the information gained with the active MASW and the ReMi methods it is possible to cover the whole frequency range of interest in the seismic site characterization 1Hz-100Hz, reaching depths greater than the 30m which are required by the international codes to evaluate the Vs^{30}. The inversion of the passive data set, collected at the same site as the previous active data (site 1), can be seen in figure 5.

In both active and passive methods described before care must be taken into account when we use inversion routines since poorly understood data and ambiguity can lead to erroneous solutions. Thus modeling, joint inversion and a priori geological knowledge can greatly improve the end result (Dal Moro and Ferigo, 2011).

A more recent alternative approach in processing data is to perform a full waveform inversion or modeling. Based on varying depth velocity models, it consists of matching a synthetic seismic record to the field seismic record. The phase velocity spectra can also be compared. Since the detailed description of this approach is not the objective of this presentation we recommend further reading on the subject (Herrmann, 1991; Romdhane *et al*, 2011; Socco *et al*, 2010). The results using this approach, for the same site mentioned before, can be seen in figure 6. Again the solution is similar to those previously presented in figures 4 and 5.

Finally a joint analysis of Rayleigh and Love-wave dispersion curves was also explored which, in theory, could give a more robust possibility to reach a common model or even provide quantitative information about possible anisotropies which, in turn, might reflect the different shear-wave velocities. Rayleigh wave dispersion depends on V_{SV} whereas Love-wave dispersion depends on V_{SH} (Dal Moro and Ferigo, (2011)). In inversion of a single data set the presence of several local minima in the inversion process is quite well-known thus gradient-based methodologies are inevitably prone to errors. Consequently the problem of the starting model that affects gradient-based inversion methods is sometimes difficult to overcome. Joint inversion of different kinds of seismic data is an optional way to both reduce the nonuniqueness of the solution and also to give a sounder data interpretation (Dal Moro, 2008). The choice of the best model made through Pareto bi-objective space (Figure 8.), supported on the symmetry of the Pareto front models with respect to the universe of considered models, constitutes an index of the general consistency of the whole inversion process (Dal Moro (2008) and Dal Moro and Ferigo, (2011)).

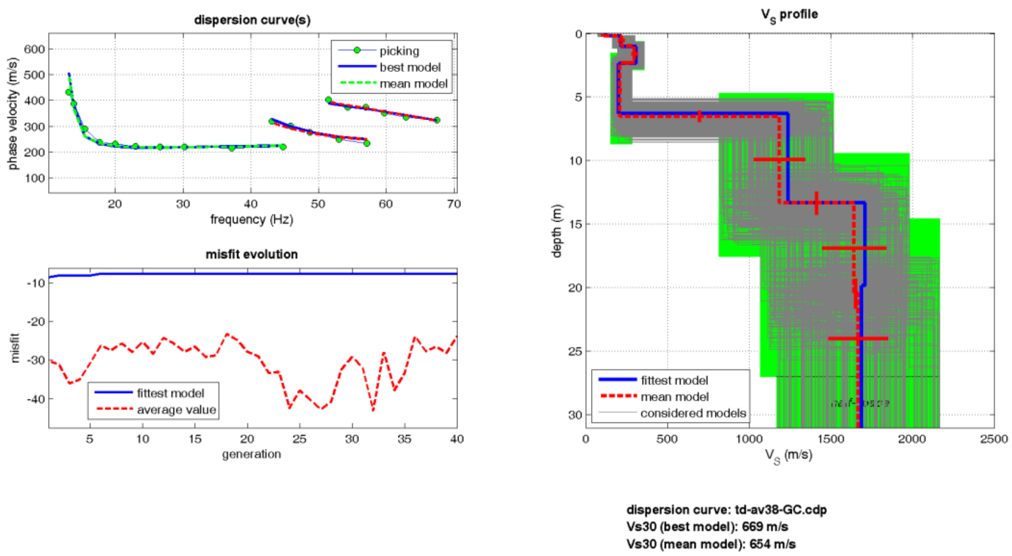

Figure 4. Inverted *Vs* section, from site 1 in figure 2, with the Vs^{30} value.
This results in a C or B ground class type soil according respectively to table 1 or table 2.

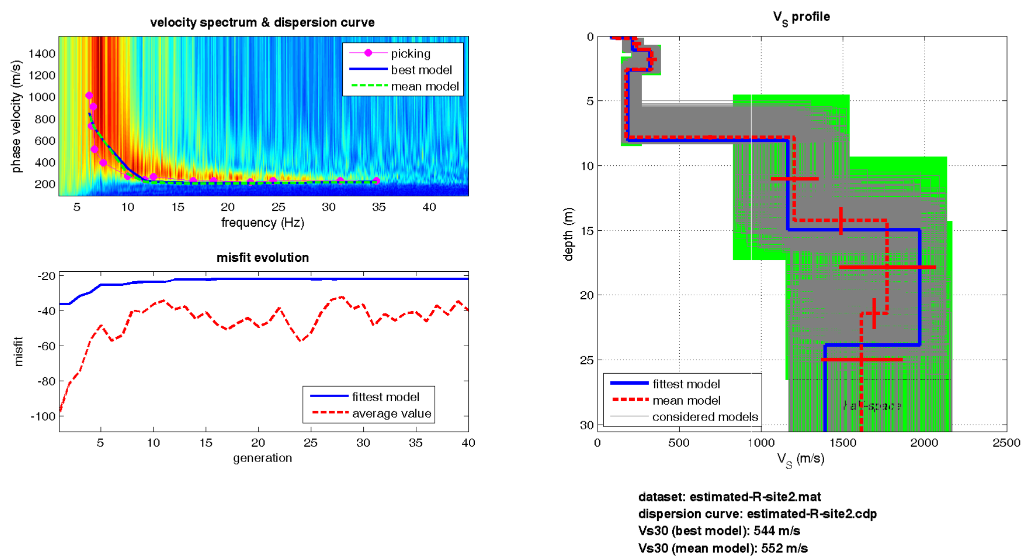

Figure 5. ReMi interpretation results section, from site 1 in figure 2, with the Vs^{30} value.

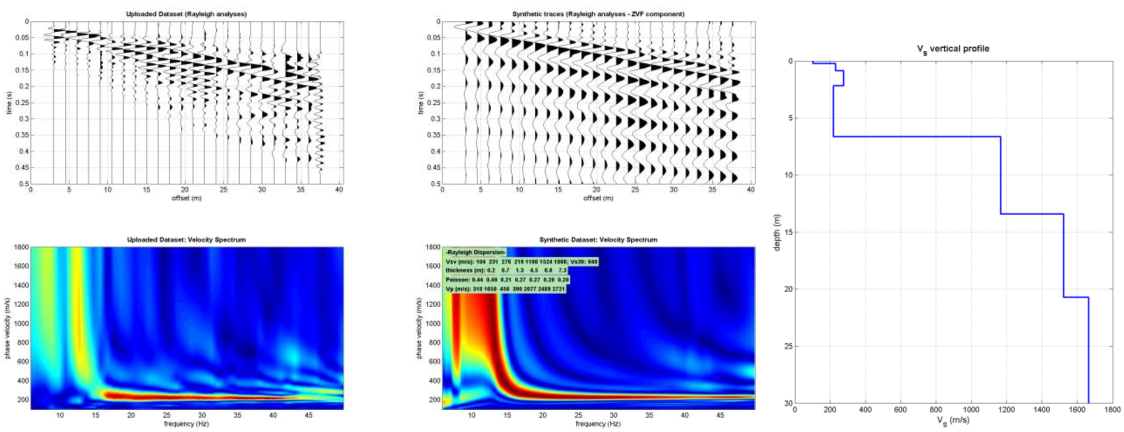

Figure 6. Full waveform interpretation results from site 1 in figure 2.

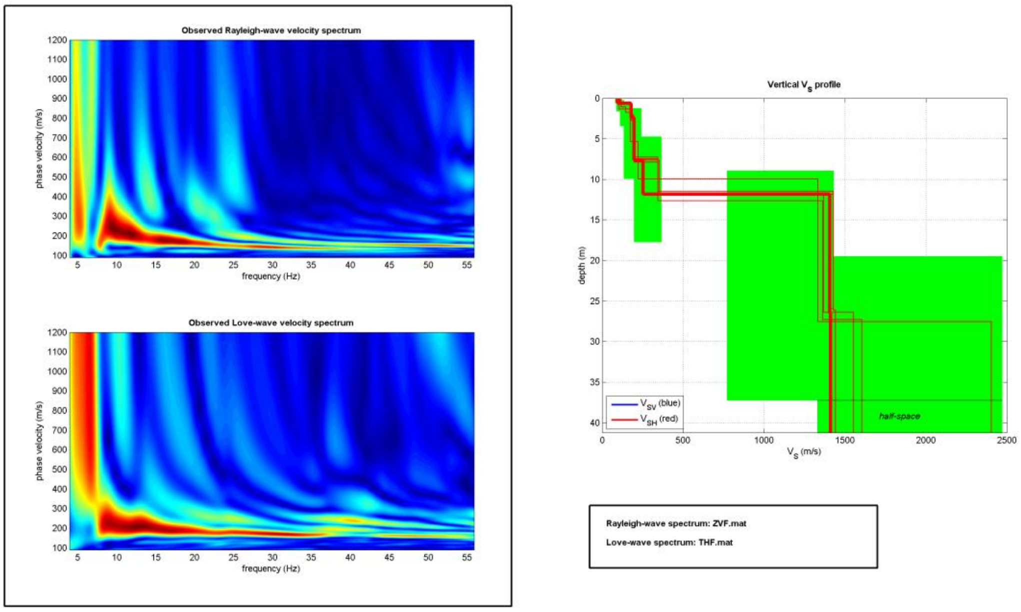

Figure 7. Inverted *Vs* section, from site 2 in figure 2, with a resulting Vs^{30} value of 417 m/s.

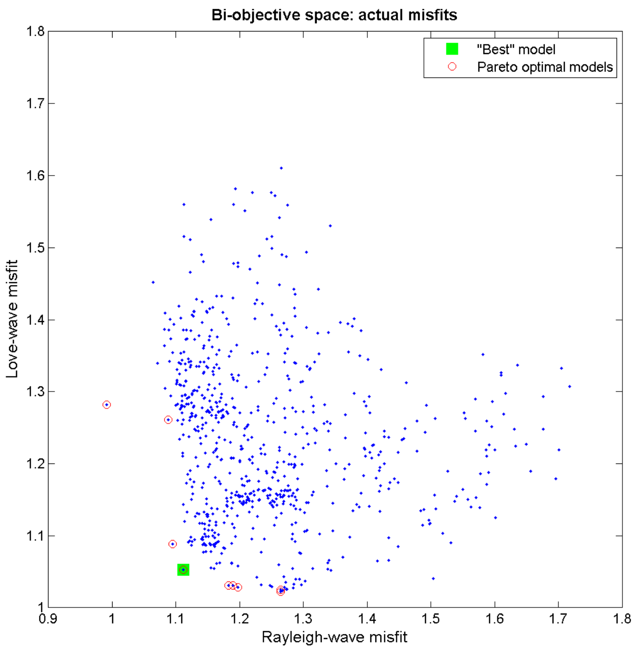

Figure 8. Pareto front models of the joint inversion of Rayleigh- and Love-wave dispersion curves. Distribution of the evaluated models in the bi-objective space (obj#1: Rayleigh-wave misfit; obj#2: Love wave misfit). Symmetry Index (S.I.) of the Pareto front models is signaled by the red circles.

4. RESULTS

As was previously mentioned the dispersive wave tests were performed within our study area and we chose for this short presentation three geotechnicaly distinct places: Weathered granite, highly weathered granite and weathered metamorphic formations. The acquisition parameters of the three active (MASW), with both vertical geophones and horizontal geophones, as well as passive (ReMi) surface wave tests were identical in geometry and are mentioned in table 2. In the case of the active surface wave data, with vertical geophones, we used a vertical source (ZVF mode according to

Herrmann (2002)) to record the Rayleigh wave components whereas the horizontal geophones were acquired with a horizontal source (THF mode according to Herrmann (2002)) in order to record the Love wave components.

Table 2. Acquisition parameters for both active () and passive surface wave tests.

	Active	Passive
Geophones spacing	1.5	1.5
Source type	3 Kg Hammer	Urban noise
Total time windows	0.5 s	16 s
Source offset	3 m	-
Number of geophones	24	24
Number of records	1	8

The data was processed by means of the *winMASW* software. The velocity profiles resulting from both the active MASW passive ReMi configuration at each test site, can be viewed in table 3.

Table 3. Vs_{30} results from the three tested sites for both active and passive surface wave tests.

Site0	Vs^{30} Active (m/s)	Vs^{30} Passive
1	650	690
2	420	450
3	510	580

As we can observe the general profile of each site follows the expected outcome that is described for each geotechnical unit depicted in figure 2. It is clear that the result from site 2 reveal the high degree of kaolinization described in the map (figure 2) whereas the other two sites are in accordance with lower expected rates of weathering. The ReMi results, although not equal in all the details, since they are obtained by generally lower frequencies, are in good agreement with the active MASW results.

5. CONCLUSIONS

The active and passive seismic surface wave testing resulted in Vs^{30} values that are in close agreement with each other and the preliminary testing of the full waveform interpretation was also consistent. Both active and passive surface wave methodologies can be applied with some degree of confidence within this noisy urban environment with crystalline geology.
Even though the different techniques gave similar and consistent results we feel that inversion can sometimes be misleading and it is the responsibility of the interpreter to control the quality of the acquired data and to ultimately conduct the analysis through both inversion and modeling in order to choose a model which makes geological, geotechnical and stratigraphic sense.
We intend to improve this microzonation map and thus contribute towards an indicative working instrument for the heritage and the civil protection institutions of Porto.

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