# ESTIMATION OF SITE SPECIFIC GROUND MOTION FOR THE DOWNTOWN AREA OF LISBON

**Helena Meireles**[1] **and Rita Bento**[2]

[1] *PhD Student, ICIST , Technical Institute of Lisbon, Lisbon, Portugal*
[2] *Associate Professor, ICIST ,Technical Institute of Lisbon, Lisbon, Portugal*
*Email: hmeireles@civil.ist.utl.pt*

## ABSTRACT:

The downtown area of Lisbon, Portugal, is an important historical site of the capital, which has been completely reconstructed with a typical XVIII century building after the major earthquake of 1755. The selected site is set on an alluvium filled valley of soft unconsolidated sediments where considerable seismic site amplification of ground motion is expected. Albeit the importance and susceptibility of the site, not much information is available in the literature for seismic ground site characterization. A collection of data has been made on geological, geotechnical and seismic surveys. Additional measurements of ambient vibrations have been done based on the H/V spectral ratio technique (HVSRT). Based on the combination of geological and geotechnical data with HVSRT, it was possible to characterize the alluvium site in terms of average shear wave velocity of the soil (*Vs,av*) and depth to bedrock (H) estimates based on the characteristic soil frequency, as well as mapping the site blocks where seismic ground amplifications are expected. The site *Vs,av* of the soil is estimated at ~194 m/s. Additional information can be obtained with the HVSRT. 1D structure assumption may predict the average response of the soil near the centre of the valley but will probably not at the edges. This is explained by the mapping of changes in the H/V curves, although not too strong 2D/3D effects are expected for this relatively shallow basin (H/*w*=0.15).

**KEYWORDS:** site characterization, ambient vibrations, H/V ratio technique, Lisbon downtown

## 1. INTRODUCTION

One key aspect in the assessment of the seismic vulnerability of a given construction at a site involves the evaluation of the effects of local soil conditions on strong ground motion. It is well known and documented the susceptibility of certain sites (e.g. Mexico City lake zone, San Francisco bay area, Lisbon downtown) to radically alter the incident ground motion causing catastrophic damage in some cases. In this way, adequate attention should be given to the characterization of the site in terms of ground parameters relevant for seismic action estimation. The most important ground parameters for seismic site characterization are the shear wave velocity of the unconsolidated sediments, the shear wave contrast between bedrock and sediments and the geometry and depth of the bedrock-sediment interface. Techniques for estimating ground parameters are usually grouped in geophysical and geotechnical (mechanical) methods. Generally, geophysical methods can differ on the possibilities and information these tests provide with the trade-off of cost. For instance, when estimating shear wave velocities, in-situ tests realized on the ground surface (e.g. seismic refraction) give global information on the medium but do not allow for an accurate definition of the shear wave velocity profile with depth; while in-situ tests realized with borehole and especially the cross-hole test, are more powerful but have as a consequence an associated high cost. Additionally, more powerful tests tend to require a bigger apparatus for the equipment, which can make them unpractical for use in densely urbanized areas, not in a systematic way at least. Geotechnical in situ tests can be a very important source of information for site characterization. The Standard Penetration Test (SPT) is certainly the most commonly employed method of this type in Portugal. These tests directly aim at obtaining soil resistance parameters but will also provide important information on stratigraphy and lithology, depth to bedrock or geometry of bedrock-sediment interface if a reasonable amount of surveys are found in an area so that a pattern is defined. Above all, mechanical surveys are an abundant source of information in urbanized areas due to construction purposes, as opposed to geophysical surveys which are not so frequently found, especially in low to medium seismicity areas.

An average estimation of the shear wave velocity of the soil for the shallowest layers of soft material can be obtained with good quality by means of measurement of ambient vibrations. A good compromise is achieved with the in-situ technique based on the measurement of ambient vibrations named H/V spectral ratio technique (HVSRT). With simple means but under specific circumstances, the technique estimates the fundamental frequency of the site from which one is able to retrieve the average S-wave velocity of the associated soil layer provided some prior knowledge is gained on the site. Techniques based on the measurement of ambient vibrations have long been applied in Japan with an important application in seismic microzonation of sites. Either single station or array station methods are used. Among the single station methods the HVSRT is the most popular. Nogoshi *et al.* [1972] first proposed the technique but this is recognized to have been widespread afterwards by Nakamura [1989, 2000] so that in the last two decades the number of related publications has increased tremendously (see D13.08 [2004] for an extensive list). The technique succinctly consists in deriving the ratio between the Fourier spectra of the horizontal and vertical components of the ambient vibrations obtained trough measurements at the surface of a specific site. The frequency at the peak of such curve ($f_0$) would be an indicative of the S-wave resonance frequency of the site and to some authors, although this is not a consensus between researchers, the corresponding peak amplitude ($A_0$) would provide a satisfactory estimate of the site amplification. Recently, it is noticeable the work developed under the scope of the research programme SESAME (2001-2004). It is seen that Nakamura himself [2000] claims the theoretical background of the technique is not clear, but the many successful experimental studies performed evidence its reliability. Understanding that the correct interpretation of the HVSRT depends substantially on the knowledge of the composition of the seismic wavefield responsible for the ambient vibrations, the research programme devoted attention to the nature and origin of ambient vibrations wavefield. Based on extensive numerical simulations (Bonefoy [2004]) and several sites investigated experimentally, the research programme confirmed the reliability of the technique in estimating the resonance frequency of the soil layer (given by $f_0$ with a deviation not higher than 20%) but claims that $A_0$ does not give a good estimate of the site amplification. Some guidelines on measurements, processing and interpretation for the implementation of the HVSRT have been delivered within SESAME (D23.12 [2005]); these have been followed in the present work. For the interpretation of the H/V curves it is relevant to point out the following: (i) the obtained results are clearer in the case of horizontally layered structures with large impedance contrasts, but become more and more fuzzy for decreasing contrasts or/and for increasing underground interface slopes; (ii) in fact, for large impedance contrasts, the H/V curve exhibits a clear peak for horizontal underground interfaces and a broader peak and generally associated lower maxima at sites with rapidly varying thickness such as valley edges (…) the amplitude of this peak is often too small to allow clear identification; (iii) as a consequence, one should always gather geological and geotechnical information looking in particular for prior rough estimations of impedance contrasts, depth to bedrock and indications of lateral variability of underground structures. Interpretation of the H/V results will be greatly enhanced when combined with geological, geophysical and geotechnical information.

Other studies have focused on the implications on the HVSRT of the fact that most sites do not have horizontally layered structures and experience 2D/3D effects such is the case of most valleys. Cornou *et al.* [2004] claims that when 3D structures can be approximated locally by a 1D structure, such as in some valley basins, then $f_0$ is able to give a good estimate of the resonance frequency of the idealized 1D local structure. On the other hand, Guéguen *et al.* [2007] points out that the simple relation linking $f_0$, shear-wave velocity $b$ and depth to bedrock H ($f_0$=$b$/4H), valid according to a 1D model assumption, in narrow sedimentary basins, may no longer be systematically interpreted according to $b$ and H owing to the potentially high error levels. Nevertheless, $f_0$ values must be considered as the frequency at which seismic motion can be amplified regardless of the 1D, 2D or 3D geometry of the site.

The scope of this paper is to gather all available information useful for the seismic ground site characterizion of Lisbon downtown, aiming at identifying the areas (blocks) susceptible to local site effects amplification of ground motion. For this purpose a research and gather of data was made comprising information on geology, stratigraphy and also available geotechnical and seismic surveys. For a detailed ground site characterization additional measurements of ambient vibrations have also been conducted based on the H/V spectral ratio technique, and these have been compared and validated with the gathered data.

## 2. PRIOR INVESTIGATION OF THE SITE

The site under study located at GPS coordinates 38’42N-09’08W is referred to the area of downtown of the city of Lisbon, Portugal. This is the “heart” of the city of Lisbon with significant historical importance mainly due to the patrimonial value of its edifications, the so-called “*Pombalino buildings*”. The site is known for the devastating damage inflicted upon the biggest natural catastrophe ever to strike Portugal, the 1755 earthquake. It sets on an alluvium filled valley which is surrounded by three hills, on the north, west and east sides and by the mouth of the river *Tejo* on the south side. A satellite view of the site can be seen in figure 1:

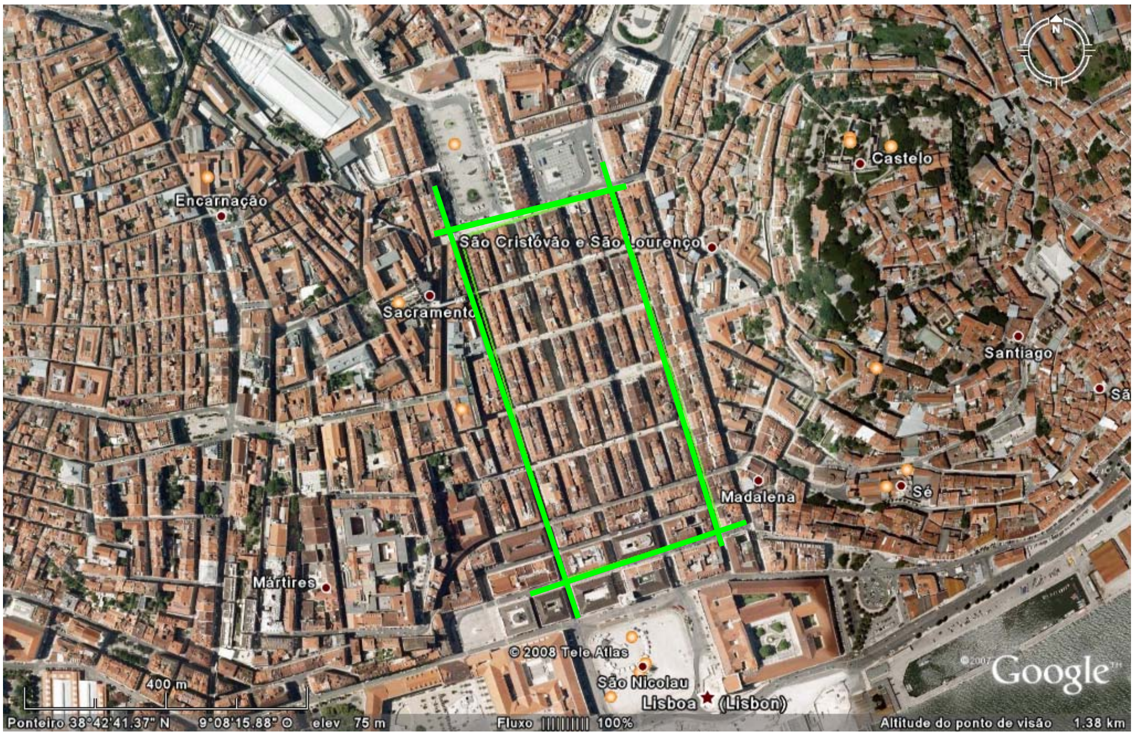

Figure 1: Location of the site within the urban area of Lisbon. The extension of the area (within the streets marked in green/grey) is about 220 m wide by 490 m long, comprising 36 blocks. Map is copyright of Google Earth.

According to the Geological map of the municipality of Lisbon (scale 1/10 000, sheet 4), see figure 2, the basement of the valley is composed of the Miocene formations named “Argilas e Calcários dos Prazeres” (these are green and grey sand material, frequently intercalated with levels of calcareous material); “Argilas do Forno do Tijolo”(these are dark grey consolidated clays); “Calcários de Entre-Campos” (these are yellowish calcareous materials) and “Areolas da Estefânia” (these are greyish fine sand materials).

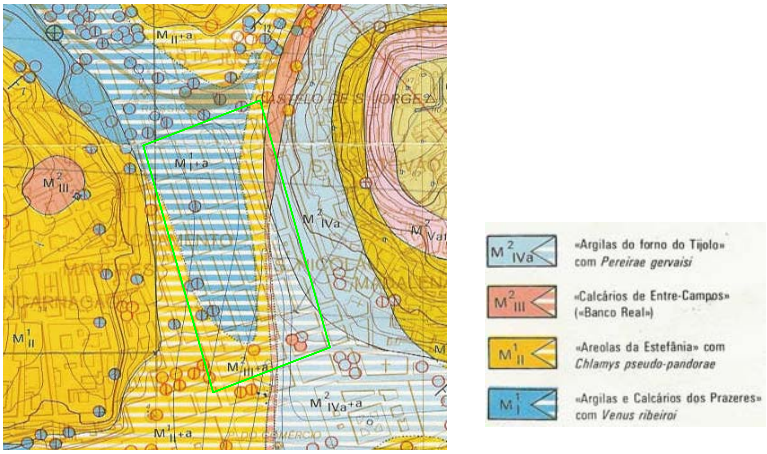

Figure 2: Geological map of the municipality of Lisbon, scale 1/10 000, sheet 4.

Geotechnical surveys gently provided by some design offices and prospecting companies, present the following information: the valley basin is filled with layers of alluvium deposits from the Holocene. These are mainly composed of fine sand with more or less quantities of mud (although clayey sand materials can also be found), defining in this way variations of alluvium layers, sometimes intercalated among each other and presenting different resistances. These have a total thickness that varies from 22.0 to 33.5 m at the centre of the basin. The topmost layer sets over the alluvium layers or directly above the bedrock formation. This layer is a normal consequence of urban activity but also resultant from the debris accumulated on the site after the 1755 earthquake. At the time, the decision of rebuilding the city at the same site where it previously stand, made the new buildings to be erected over the remains of the destroyed city making also the ground surface level to raise some meters over sea level. It is thus found this topmost material to be very heterogeneous, with sporadic elements of stone or debris of wood or ceramic fragments, all set in a matrix of a sandy clay material. This layer thickness varies from 1.5 to 9.0 m over the entire site.

Depths to bedrock values obtained with the several surveys consulted show that the thickness of the soil layer slightly increases towards south. At the centre of the valley, the depth to bedrock will be 31.5 m at the northern side and increasing up to 42.4 m at the south side of the site, in a length of ~490 m. The width of the valley is $w$~250 m. This may be considered a relatively shallow valley with a depth to width ratio of $H/w \sim (31.5+42.4)/2/250=0.15$. The geotechnical surveys available consisted essentially in SPTs. The results present very broad values of the soil resistance, given by the number of blows in the tests, varying from 4 to 60 in the topmost layer of deposits or ranging between 2 and 60 in the alluvium layers. Even if this aspect reveals the heterogeneity of the materials it is also certain that the higher values of the number of blows are associated with the sporadic debris encountered for the topmost layer and that generally this layer is softer than the alluvium one. The geotechnical surveys consulted have also indicated the Miocene formation “Argilas do Forno do Tijolo” to present characteristics of a stiff soil, soft to hard rock behaviour for the formation “Calcários de Entre-Campos” and stiff soil to soft rock behaviour for “Areolas da Estefânia”. Ground water level is generally found at the end of the topmost layer and at 6.5 m (north side) to 2.5 m (south side) over sea level.

Even though seismic site effects are known to be a concern at this site, not too many studies have focused on the seismic response of the basin. A relevant but wide-ranging study was done by Teves-Costa *et al.* [1995]. In order to evaluate the predominant frequencies of the soil formations, the HVSRT was applied to the city of Lisbon with 114 points measured in a range of frequencies from 0.5 to 12 Hz. A detailed analysis though revealed complicated since not much was known about the underlying formations but a general comparison was made between the HVSRT results and the geological map. In the area of downtown it was found a predominant frequency of about 2 Hz.

## 3. H/V SPECTRAL RATIO TECNIQUE APPLIED TO THE SITE

### *3.1. Measurements and processing*

The HVSRT has been applied to the site in a total of 10 measurement points intentionally placed at the locations where geotechnical surveys had been conducted; in this way a direct comparison is made between the results of the recordings and the geotechnical and geological data. The location of each measurement point (DN, PF, P12, P11, P10, P89, SC, P6, S2a, S3) and the location of the geotechnical surveys conducted on the area (DN, P13, PF, P10, P11, P12, P6, P7, P89, SC, S2a, S2b, M, B) can be seen in figure 3. The measurement campaign lasted 3 nights; measurements were conducted at night so as to avoid perturbations due to human activity; 30 min recording time was considered for each point; few to moderate noise from pedestrians, cars, trucks or buses was observed; none to few wind (up to 5m/s) and no rain was observed; it was estimated the location of underground structures of normal urban activity (pipelines), the *Pombalino* sewage system and the car park in *Praça da Figueira*. Care was taken so as to avoid placing the sensor over these underground structures. The sensor used was the broadband seismometer CMG-40TD from Güralp Systems Limited, designed for medium noise sites, with 1s-50Hz response options and 3-component model and associated digitiser CMG-DM24. This is not expected to require a long stabilization time. The sampling rate of recordings was 50 Hz. The computations of H/V ratios were facilitated by the available free software GEOPSY downloadable at http://www.geopsy.org. The software performs the computation based on the three files of a recording (North-South (NS), East-West (EW), Vertical (V)) calculating for each individual time window of measurements the $H/V = \left(\sqrt{(NS^2 + EW^2)/2}\right)/V$ spectral ratio, further calculating the average H/V of all windows and estimating the associated standard deviation. Associated processing such as DC-offset removal, filtering, smoothing, etc, is also performed. The data has only significance, due to sampling frequency, window length and equipment functionalities, between the interval of 1-20 Hz, which is also the interval of frequencies of interest for the specific soil profile. The time windows were selected manually for better accuracy. In order to obtain a clearer peak, transient loading was removed in the time windows and this was done by visual inspection of the data. No overlap has been considered for two subsequent windows.

Figure 3: Location of the geotechnical surveys (red/grey dots) and HVSRT measurement points (black dots).

### *3.2. Interpretation and discussion*

According to the recommendations on the interpretation of the noise data outlined in D23.12 [2005], the criteria for reliability of results and for obtainment of a “clear peak” were followed so as to identify the peak frequencies, $f_0$, see table 1. From the identified peak frequencies, it was estimated the average shear wave velocity of the unconsolidated sediments (*Vs,av*) where the depth to bedrock (H) was known, such was the case at points PF and SC. The depth to bedrock was taken from the geotechnical surveys collected and considered as being the depth where of the first number of blows of two consecutive blows higher than 60 was reached in the SPT results (denial). It can be seen how the two obtained values for *Vs,av* are similar attesting the accuracy of the results. The *Vs,av* is then estimated at ~194 m/s. For other points, such as DN and P11, the depth to bedrock was estimated based on *Vs,av*. Nevertheless, in the case of DN two peaks were obtained ($f_0$ and $f_{0*}$) and in the case of P11 the peak frequency could not be discerned within the interval 1.44to1.66 Hz, giving that H could not be estimated with more precision. The two peak case could be an indicative of two large impedance contrasts (>~4) at two different scales. However, from the several cases analyzed in the SESAME project it is seen that the two frequencies should be sufficiently apart for this to be the case. It is thus thought this to be explained by the location of the point relatively close to the left edge of the valley, by contrast to the “clear peak” with larger amplitude obtained at point PF located at the central part of the valley. Some other points (P12, P89, and S2a) revealed a "broad peak" case, where no precise value of $f_0$ could be found but showing significant site amplification. Significant site amplification is foreseen for amplitude $A_0$ higher than 2 where an impedance contrast of ~4to5 is expected in this case (D23.12[2005], Bonefoy Claudet [2004]). No peak case means the curve is flat over all frequency range examined, in these cases if the geotechnical data indicates this is a hard rock site then no amplification is expected at these points.

Table 1: Summary of the results with obtained peak frequencies and estimated ground parameters.

| Meas. Point | H/V curves results | H (m) | *Vs,av* (m/s) |
|---|---|---|---|
| DN | Reliable/"Multiple peak" $f_0$=1.55 and $f_{0*}$=2.21 Hz | ~31.3 or 21.9 | - |
| PF | Reliable/"Clear peak" $f_0$=1.53 Hz | 31.5 | ~193 |
| P11 | Reliable/"Clear peak" $f_0$=1.44to1.66Hz | ~33.7to29.2 | - |
| SC | Reliable/"Clear peak" $f_0$=1.28 Hz | 38.0 | ~195 |
| P12, P89, S2a | Reliable/"Broad peak" | - | - |
| P10, P6, S3 | Reliable/No peak | - | - |

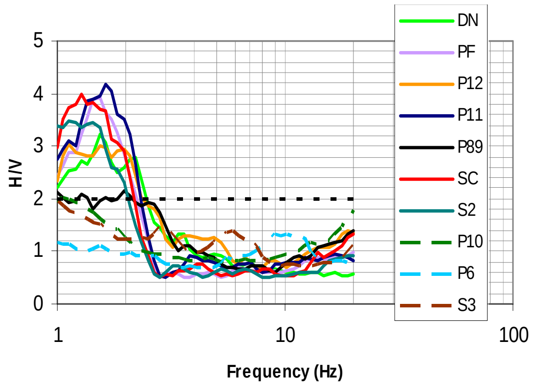

Figure 4: Comparison of the obtained H/V curves in all measurement points.

A "broad peak" case may happen because of the presence of unknown underground structures, possible marked underground slopes or be explained by the proximity to a valley edge. It is noticeable that in all the points analyzed all "broad peak" cases (and one "multiple peak" case) were found at an edge of the valley while all "clear peak" cases were found where the valley basin centre location is probable. It is thus thought this to be the reason for the appearance of these broad peaks with lower amplitude values, as predicted. In figure 5(a) to (e) has been done a compilation sketch of the ground profiles based on all the geotechnical data gathered, information from City Hall on interpretative geological profiles and additional information provided by the HVSRT results. The particular location of the measurement point S2a in the same line as points SC and P11, would lead one to believe that S2a would be placed at the centre of the valley and the same "clear peak" would be expected as for the former points. Nevertheless, by careful inspection of geological and geotechnical data at points S2a and S2b it can be seen that measurement point S2a is in fact close to an extremity of the valley found at its southwest side (to the point), explaining the appearance of such "broad peak" in the H/V results. Geological data indicates different bedrock formations of the Miocene for points S2a and S2b; geotechnical surveys at these points confirm these results. Figure 5(d) evidences the difference in depth to bedrock of the two close points S2a and S2b; while soil thickness at point S2a is 42.4 m and "Areolas da Estefânia" formation is found, at point S2b soil thickness drastically reduces to 15.0 m (note that a masonry wall is found between the recent deposits layer) after which one meter thick of "Argilas do Forno do Tijolo" is intersected followed by "Calcários de Entre-Campos" formation. A flat curve is obtained for points S3, P6 and P10; soil thickness at these points is low, respectively 1.5 m, 6.0 m and 10 m (given for S3 by the average between points P6 (6.0 m) and S2b), meaning no relevant site amplification is expected.

By direct comparison of all the obtained H/V curves (figure 4, note that associated H/V standard deviation curves are not plotted for better comparison between curves) it is possible to observe clearly two distinct groups of curves, which are presented in full and dashed lines. These are grouping the points where there is expected site amplification (DN, PF, P12, P11, P89, SC, S2a) and where there is not (P10, P6, S3). In figure 3 it can be seen additionally the mapping of the blocks according to this grouping: former points in blank and latter in diagonal stripes. At the former it is noticeable that the amplification is restricted to the same frequency band ~1-2.5 Hz. Based on the value of *Vs,av* obtained and on the previous observations, Eurocode 8 [2004] based soil class C or D could be appointed to the former points while soil class A or B would be attributed to the latter.

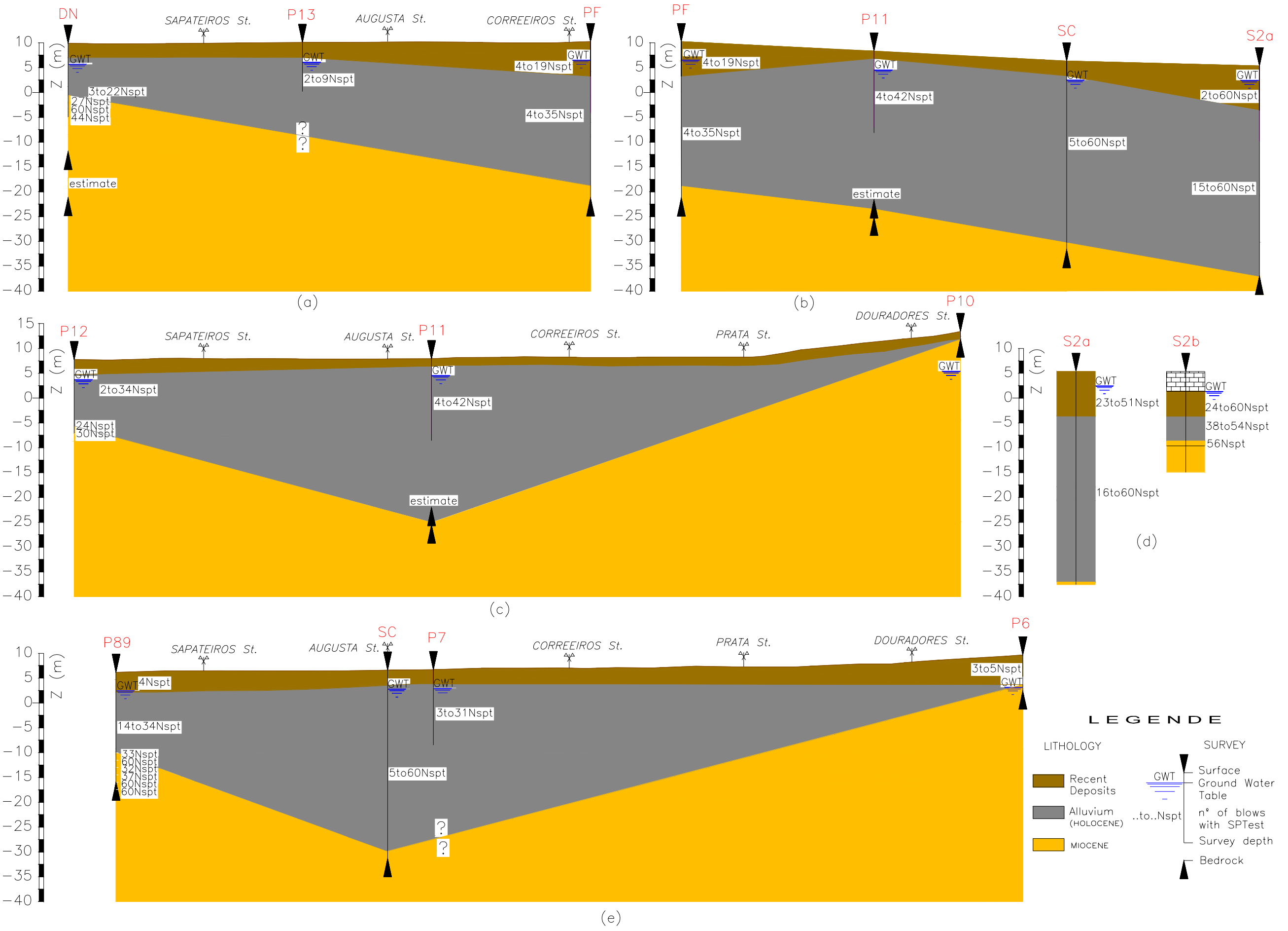

Figure 5: Interpretative cuts of ground profile (no horizontal scale).

## 4. CONCLUSIONS

From the procedure carried out in the present study, based on the combination of geological and geotechnical data with HVSRT, it was possible to characterize the alluvium site of downtown area of Lisbon in terms of shear wave velocity of the unconsolidated sediments, associated estimated impedance contrast between bedrock and sediments and general geometry and depth of the bedrock-sediment interface, as well as mapping the site blocks where seismic ground amplifications are expected. The site *Vs,av* of the soil, unknown in the literature, is estimated at ~194 m/s, and will not diverge more than 20%. It is assumed reasonably that the same sedimentary process formation has taken place in the basin so that similar soil properties are found throughout the site (as indicated by the geotechnical data) and the obtained *Vs,av* of the soil is the representative value for the all site.

Apart from the direct estimation of *Vs,av* of the soil profile, HVSRT may give us other important information. For instance, testing of the hypothesis of a 1D structure (for numerical modelling purposes) could also be performed by mapping the change in $f_0$ and shape of the H/V curve in the area, as pointed out by Fäh *et al.* [2003]. As it is expected, 1D structure assumption may predict the average response of the soil near the centre of the valley but will probably not at the edges and this could be mapped by the appearance of "broad peaks" in the HVSRT results. On the other hand, Guéguen *et al.* [2007], based on results obtained in the Grenoble basin (H/*w*=0.25) with strong 2D/3D effects, states care must be taken when using the technique as an exploration tool since basin geometry can disturb $f_0$ measurements using the HVSRT. Interpretation of $f_0$ values in terms of bedrock depth gave rise to estimation errors of about 10% found at the central parts of the valley. Since the site of Lisbon downtown has much less pronounced 2D/3D effects (H/*w*=0.15), one can reasonably assume an even lower error has been accomplished on the estimation of ground parameters in the analyzed site.

One of the most important conclusions to point out is the easiness in obtaining important site characteristics with very few resources and contrary to more common geophysical prospecting techniques, which would not be suitable for the academic work being conducted. The HVSRT was found to be a practical mean of site characterization in the analyzed case study, consistent, expedite and with associated low-cost.

## 5. AKNOWLEDGEMENTS

The authors strongly acknowledge the indispensable contribution to this work of the following parts: SOPECATE (Eng. Teresa Simões), Tecnasol FGE (Eng. Pedro Lopes and Dr. Paulo Rodrigues), COMPOREST, Geocontrole (Dr. Carlos Sacadura), Rodio (Eng. Ricardo Nicolas), CML-Câmara Municipal de Lisboa (geology dept. and Baixa-Chiado dept.), Prof. João Fonseca and Prof. Sousa Oliveira and Eng. Joana Pinho.

## REFERENCES

Bonnefoy-Claudet, S. (2004). Nature du bruit de fond sismique: implications pour les études des effets de site. *PhD Thesis, Joseph Fourier University, Grenoble, France*, 241 pages.

Cornou C., Kristek J., Bonnefoy-Claudet S., Fäh D., Bard P.-Y., Moczo P., Ohrnberger M., Wathelet M. (2004). Simulation of seismic ambient vibrations: II. H/V and array techniques for real sites. *Proc. 13th world conference in Earthquake Engineering, Vancouver, paper 1130.*

Deliverable D13.08 of the SESAME European Project. (2004). Nature of noise wavefield. (Available on the SESAME web site : http://SESAME-FP5.obs.ujf-grenoble.fr.).

Deliverable D23.12 of the SESAME European Project (2005). Guidelines for the Implementation of the H/V Spectral Ratio Technique on Ambient Vibrations Measurements, Processing and Interpretation. (Available on the SESAME web site: http://SESAME-FP5.obs.ujf-grenoble.fr.).

EN 1998-1, Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings, (2004). CEN, Brussles.

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

Guéguen P., Cornou C., Garambois S., Banton J., (2007). On the limitation of the H/V Spectral Ratio Using Seismic Noise as an Exploration Tool: Application to the Grenoble Valley (France), a Small Apex Ratio Basin. *Pure appl. Geophys*, **164**, 115-134.

Nakamura, Y. (1989). A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *R.T.R.* **30:1**, 25-33.

Nakamura,Y. (2000). Clear identification of fundamental idea of Nakamura's technique and its applications. *12th World Conference on Earthquake Engineering.*

Nogoshi M., Ogoshi M. and Igarashi T. (1972). On the amplitude characteristics of microtremor (Part 2). *Journal Seismol. Soc. Japan*, **24**, 26-40. (in Japanese with English abstract).

Software Sesarray package (Available on the web site: http://www.geopsy.org).

Teves-Costa, P., J.A. Costa Nunes, L. Senos, C.S. Oliveira and D. Ramalhete, (1995). Predominant Frequencies of Soil Formations in the Town of Lisbon Using Microtremor Measurements, *Proc. 5th Int. Conf. on Seismic Zonation*, vol **II**: 1683-1690, Nice (France).