ESTIMATION OF SITE EFFECTS USING MICROTREMOR MEASUREMENTS AND ANALYTICAL MODELLING – APPLICATION TO THE LOWER TAGUS VALLEY, PORTUGAL

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SUMMARY

In order to characterise the seismic response of the Lower Tagus Valley, a microtremor survey was carried on for the entire region, giving the natural frequencies of the shallower geological formations. Further, detailed microtremor surveys were carried out for some selected towns, looking for local effects. Theoretical 1D and 2D modelling was also performed based on the vertical incidence of a SH-wave. It was possible to observe a strong correlation between the surface geology and the microtremor results. Damage distribution of historical earthquakes was compared with the obtained results. It is believed that the geometrical configuration of the valley also contributes to emphasise the differences between the several towns of this valley. The obtained results support the application of the Nakamura's technique, using microtremor measurements, on microzonation studies, which could be very important on urban and land planning. The computation of the theoretical seismic response of the valley seemed to be very important on the estimation of the ground motion to be expected in the occurrence of a large event. The applied methodologies are very important, especially in regions with low seismicity but with high seismic risk, which is the case of the Lower Tagus Valley.

INTRODUCTION

The Lower Tagus Valley is located in the central part of Portugal and it corresponds to the last part of the Tagus river basin. It is oriented in a NE direction, and it reaches the northern part of the Lisbon town. The studied region takes up an area of approximately 3200 km^2.

The seismicity pattern of this region is characterised by several small and medium earthquakes, and some strong earthquakes that occurred in historical times. The last big one struck April 23, 1909, and destroyed several small towns located in the valley. The main seismogenic source able to produce large earthquakes within this region is the Lower Tagus Valley Fault. This fault is part of a complex fault system which, in fact, constitute the seismogenic zone (Cabral, 1995). Several historical earthquakes prove the tectonic activity of this fault system. The major fault is a strike-slip fault with 120 km length, close following the course of the river, but which is not directly visible on the field due to the thick cover of the valley. However, it was detected by seismic methods and it can be delineate by satellite photography (Cabral *et al.*, 1988; Cabral, 1995). This fault system is presented in figure 1, together with the local seismicity.

During the last years, the Lower Tagus Valley region exhibits a moderate to low seismicity. However, this region was also violently struck in the past by earthquakes with a far source as, for example, the 1755 earthquake originated in the Atlantic Ocean near the Gorringe Bank (about 250 km far away). About 3 million of inhabitants live in this valley, which correspond to almost one third of the total population of the country. Due to the concentration of population and taking into account the historical seismicity, this region is considered as a high seismic risk zone.

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To better characterise the seismic behaviour of this zone, two different research projects have been recently developed. This paper will present the results of two main tasks performed under these projects. The first one consisted on the execution of microtremor surveys: a large scale one, carried on for the entire region, giving the natural frequencies of the shallower geological formations; and detailed microtremor surveys, carried on for some selected towns, looking for local effects. The second task consisted on the theoretical modelling of the valley, in order to estimate its seismic response during the occurrence of a strong earthquake.

Some of these results were already presented in previous papers (Teves-Costa and Senos, 1996; Teves-Costa *et al.*, 1997a; 1997b; Ramalhete *et al.*, 1998). However, due to their importance to discuss and understand the whole problem, they will be presented here.

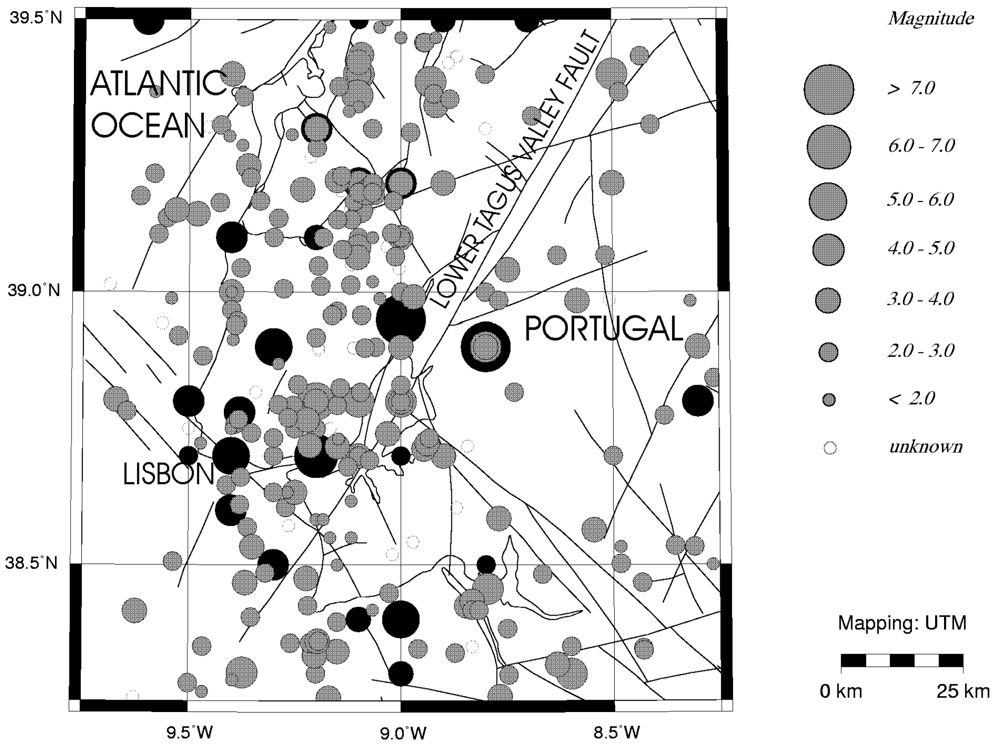

Figure 1 – Historical and instrumental seismicity, updated to December 31, 1998, and presented over the neotectonic map of Cabral *et al.* (1988). Historical events are represented as black circles and instrumental events (since 1920) are represented as grey circles.

LOCAL SEISMICITY

The Lower Tagus Valley region is characterised by a moderate seismic activity with several small and medium earthquakes and some strong earthquakes. Figure 1 presents the historical and instrumental seismicity of this region.

Reports on historical seismicity refer two main events, in 1344 and the 1531, which caused severe damage in the entire region and, in particular, in the Lisbon town. According to the damage distribution, the estimated magnitude for the 1531 earthquake is close to 7.0. During this century, only a strong earthquake occurred within this zone, on April 23, 1909. It caused 30 victims and destroyed several small towns located in the valley. The estimated moment magnitude was 6.2 and the epicentral Mercalli Modified Intensity reached the level IX. It was the biggest earthquake that occurred during this century in the central part of the country.

By the analysis of figure 1 it is easy to observe that the biggest earthquakes occurred during historical times. The instrumental seismicity, recorded since 1920, presents only a few earthquakes with magnitude greater than 4.0.

However, it is clear that the Lower Tagus Valley Fault is still a main seismogenic zone. Martins and Mendes-Victor (1993) found a return period of 84±13 years for an earthquake with magnitude 7.0 originated in a large area which includes the Lower Tagus Valley region.

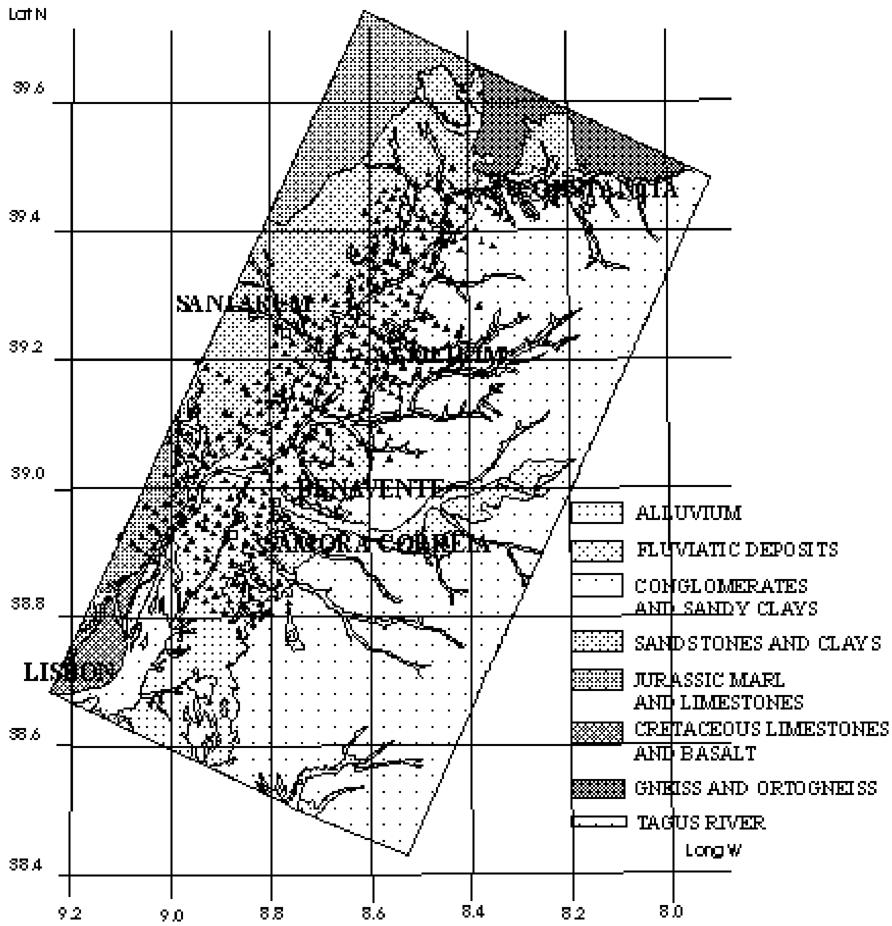

Figure 2 – Sketch of the geological map of the Lower Tagus Valley region (adapted from SPG, 1992). The small triangles indicate the recording sites of the large scale microtremor survey.

GEOTECHNICAL AND GEOLOGICAL CHARACTERIZATION

Figure 2 presents a sketch of the geological map of the studied zone in the Lower Tagus Valley. This is mainly a large plateau, slightly dipping to the river. From west to east it is possible to identify four distinct natural zones (Zbyszewski, 1953-1979): (1) the Miocene and Pliocene plateau of the right margin; (2) the plain where the river flows; (3) the fluviatic terraces of the left margin; (4) the Miocene and Pliocene plateau of the left side of the river. The plateau on the left margin is much larger than the one on the right margin.

The most representative soils belong to the ceno-antropozoic cover. From top to bottom they are composed by recent alluvium, quaternary deposits of fluviatic terraces, Pliocene sandstone and conglomerates, and a thick layer of sandy clays and sandstone. These geological formations, that cover the Tagus basin, were deposited over hercynian bedrock (probably the basement). On the right margin, after the Pliocene and Miocene formations, Eocene, cretaceous and Jurassic formations outcrop, mainly composed by silts, clays, marls and limestone. In the southern part of the valley, the Jurassic formations are very close to the river and, in Lisbon, cretaceous limestone and basalt reach the river margin (Zbyszewski, 1953-1979).

In spite of the good knowledge of the surface geology, the deep structure of the valley is not well known and, up to now, only two deep geological sections are available in Ribeiro *et al.* (1979) and Mendes-Victor and Hirn (1980). Compilation and analysis of available information was performed using also the results of other research projects under development. In order to estimate the depths and thickness of the different geological formations, several geological logs were analysed (Marreiros, 1999). Geoelectric vertical sounding profiles were also analysed looking for a correlation between the electrical resistivity and the lithology (Gonçalves *et al.*, 1997).

These interpretations allowed a better definition of the boundaries between the different geological layers and the identification of probable geological faults. Shallow seismic refraction profiles were also performed, giving the estimation of the seismic velocities of the shallower formations (Carvalho *et al.*, 1998). All these information allowed the definition of a structural model for the Lower Tagus Valley, which was further used in the numerical calculation.

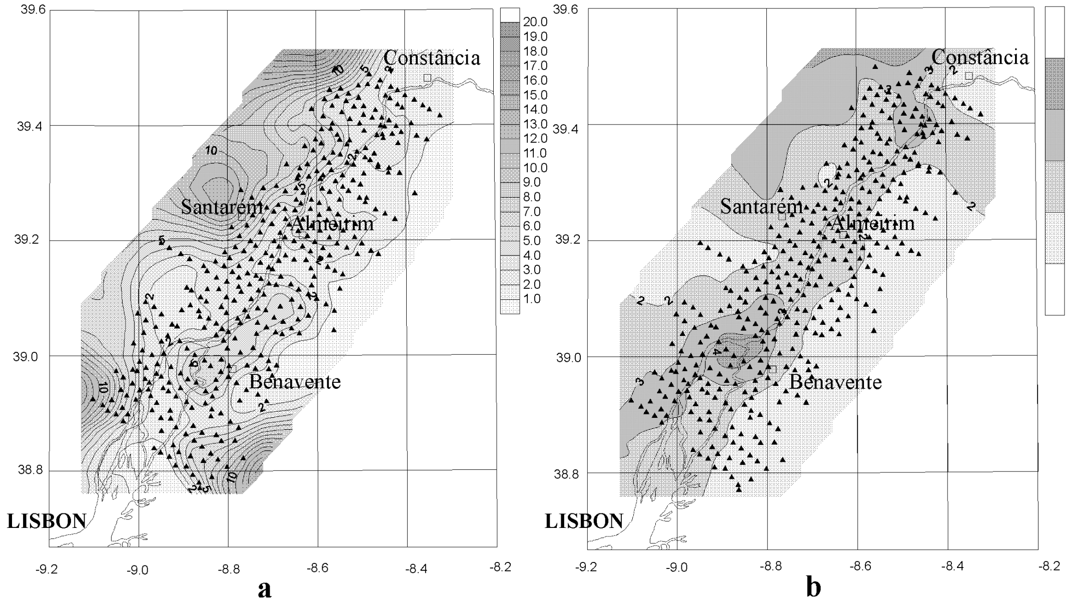

Figure 3 – Predominant frequencies (a) and respective amplification factors (b) for the Lower Tagus Valley region, obtained with microtremor analysis (after Teves-Costa *et al.*, 1997a).

MICROTREMOR SURVEYS

A microtremor experiment was carried out in the Lower Tagus Valley region in 1996. Five minutes of seismic noise were recorded at 380 sites, according to a grid of 2 km wide (see figure 2). A detailed description of the experiment, as well as data processing and analysis methodology, were already presented in former papers (Teves-Costa et al, 1995; Teves-Costa and Senos, 1996; Teves-Costa et al., 1997b). The data were analysed according to Nakamura's technique (Nakamura, 1989; 1996). Figure 3 summarises the obtained results.

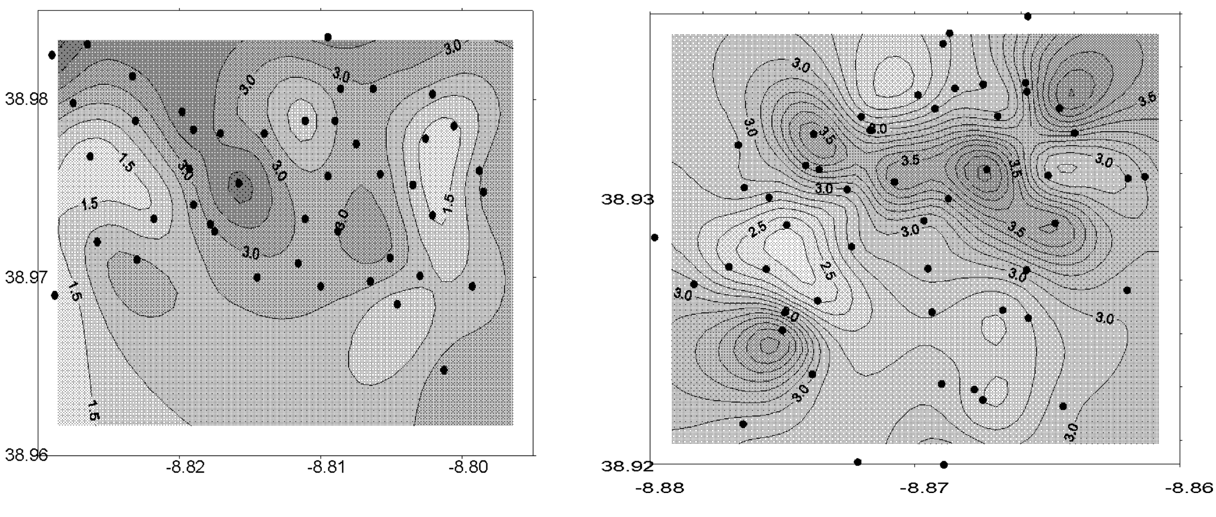

Figure 4 – Predominant frequencies for Benavente (on the left) and Samora Correia (on the right).

Detailed microtremor surveys were also performed for two small towns in the valley, located over the alluvium cover, Benavente and Samora Correia (located in figure 2). These two towns were almost completely destroyed during the 1909 earthquake. Figure 4 presents the results of the microtremor analysis.

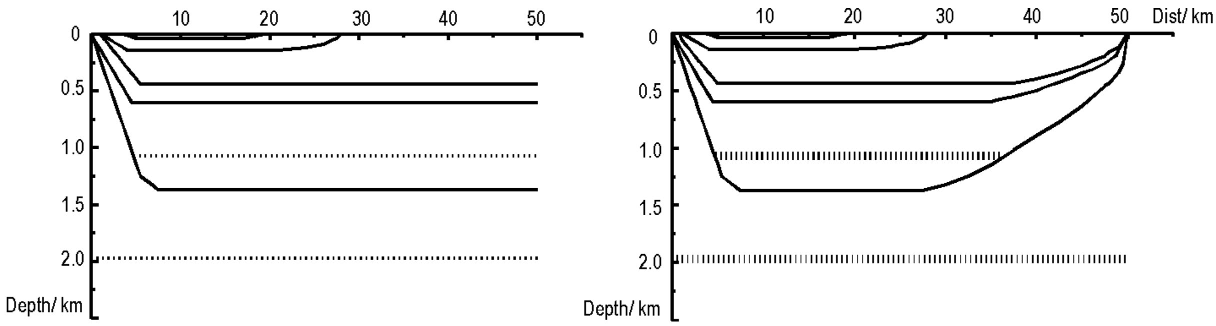

Figure 5 – Layers geometry of the Lower Tagus Valley basin. (a) On the left: structural model estimated from the geological and the geotechnical characterisation; (b) on the right: simplified structural model used in the numerical computations. The maximum thickness of the shallower layer is 40 m. S-wave velocities for the different layers are: V1= 230 m/s; V2= 750 m/s; V3= 1150 m/s; V4= 1330 m/s; V5= 1550 m/s; V6= 1730 m/s; V7= 2900 m/s; V8= 3500 m/s (basement).

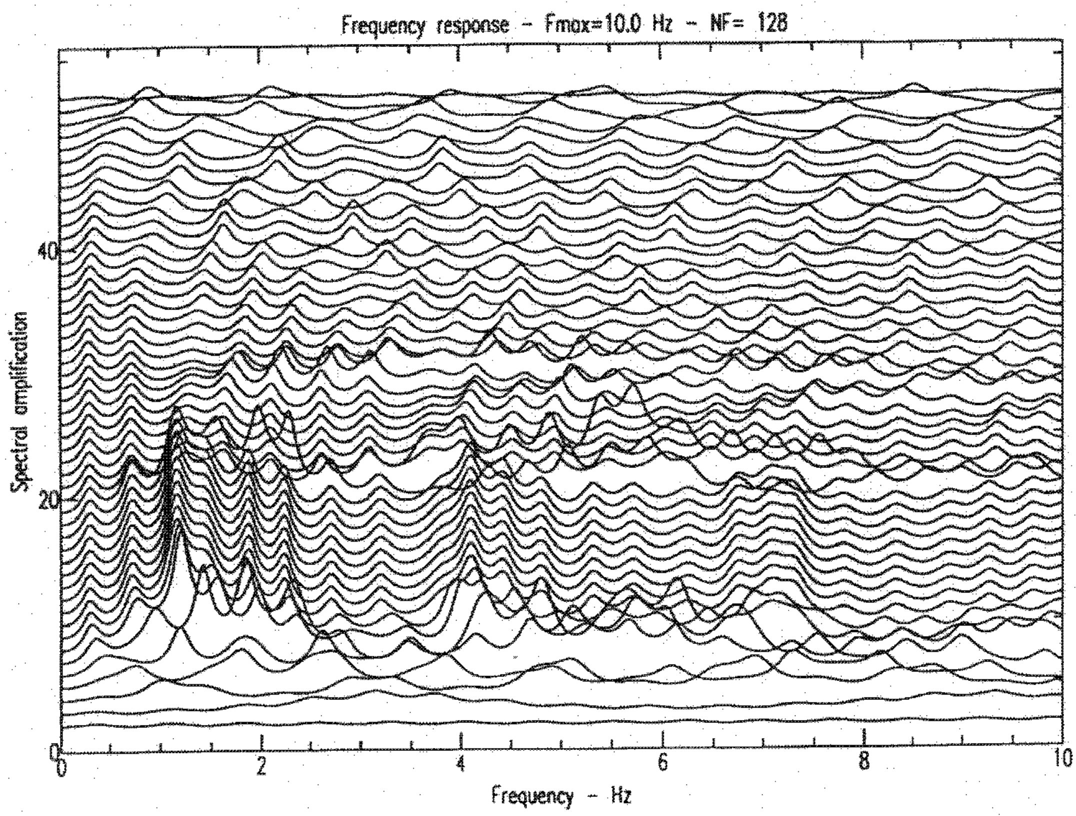

Figure 6 – Spectral amplification obtained for 50 points equally spaced along the cross-section valley, using the Thomson-Haskell 1D modelling.

NUMERICAL MODELLING

Taking into account all the geotechnical and geological information, a structural model for the Lower Tagus Valley basin was proposed (figure 5a). The valley presents a sharp asymmetry, with a larger plateau in the left margin and, obviously, its deep structure varies also along its width. However, the algorithm used to perform the 2D modeling requires that all the layers reach the surface, although allowing horizontal stratification inside each geological formation. Figure 5b presents the structural simplified model used in the numerical computations.

The 1D modeling was performed for 50 points equally spaced along the valley, using the Thomson-Haskell method (Haskell, 1960). Figure 6 presents the 1D response of the valley to a vertically incident SH-wave. This result shows the amplifications of the lower frequencies (up to 2 Hz), due to the shallower structure, and the amplifications of the higher frequencies (around 4 Hz), dependent on the deep structure.

To estimate the 2D response of the valley, the Aki-Larner method was used (Aki and Larner, 1970; Bard and Bouchon, 1980). It was considered the incidence of a vertical SH-wave. Figure 7 presents the results obtained in 100 points equally spaced along the valley, in the time domain and in the frequency domain.

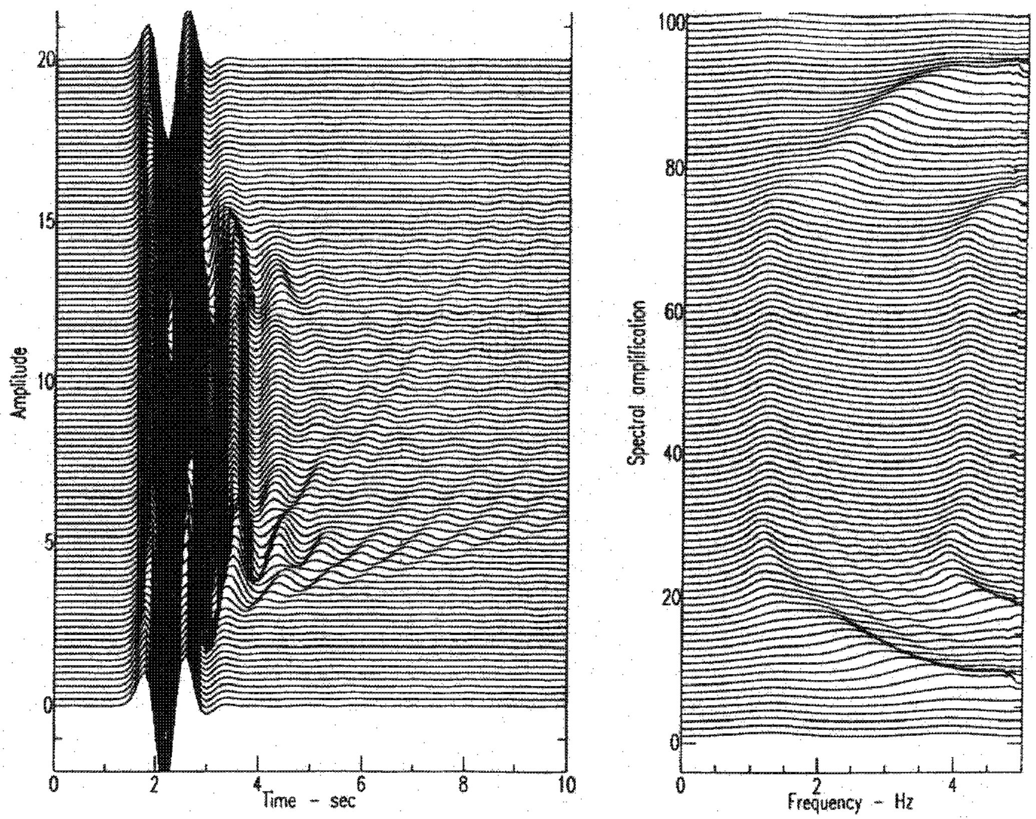

Figure 7 – 2D response obtained in 100 points equally spaced along the cross-section of the valley. (a) On the left: synthetic seismograms; (b) on the right: spectral amplification.

DISCUSSION

The microtremor analysis gave the predominant frequencies of the whole valley: in the alluvium deposits, near the river, the peak frequency lies between 1.5 and 2.5 Hertz; the high peak frequencies (up to 5.5 Hz) appear on the right margin, near the more consistent formations (sandstone and clays). However, the spectral amplification factors are not very high, reaching 3 near the river, and less than 2 in the more distant sites.

The detailed microtremor surveys, performed for two small towns located over the alluvium cover of the valley, gave the predominant frequencies ranging from 1.5 to 3.5 Hz (see figure 4 – Samora Correia). According to their location in the valley, the expected predominant frequency should be 3.0 Hz (see figure 3). In spite of the homogeneity in the surface geology, it was possible to identify different peak frequencies. These different frequencies could be related with different thickness of the alluvium cover, or with the existence of local heterogeneity due to small differences on the physical properties of the surface layers (different densities, changes in the water level, existence of strange buried materials, etc.).

The numerical computations show two dominant frequencies on the seismic response of the valley. Both 1D and 2D computations showed spectral amplification for 2 Hz and 4 Hz. As already pointed, the lower frequency is due to the influence of the shallower stratification, while the higher frequency is dependent on the structure of the deep layers.

Damages on past earthquakes could be related with these dominant frequencies. The building stock of most of the small towns located in this valley was composed by low rise houses (1 or 2 stories) constructed in masonry stone, usually with a predominant frequency between 2.5 and 3.5 Hz. It is not difficult to suppose that these buildings could easily resonate during the occurrence of a near earthquake.

CONCLUSIONS

The application of the Nakamura's technique, using microtremor measurements, seems to be very useful to study the regions with low natural seismicity. The predominant frequencies are in good correlation with the surface geology, and they are sensitive to the change of thickness in the alluvium and soft deposits. The correlation with damage distribution in past earthquakes is also reasonable. These results support the use of this technique on microzonation studies, which could be important on urban and land planning.

The analysis of different kind of geological, geotechnical and seismic information, improved the knowledge of the structure of the Lower Tagus Valley. This knowledge allowed the computation of theoretical seismic responses of the valley, which are very important to estimate the surface seismic movement to be expected in the occurrence of a large event. The application of this methodology is very important, especially in this region were big earthquakes present a long return period, but which exhibits a high seismic risk, according to historical reports, population distribution and its socio-economic importance. It is believed that the geometrical configuration of the valley contributes to emphasise the differences between the seismic behaviour of the several towns of the valley. Consequently, it is obvious that additional geological and geotechnical research is still required in order to improve the structural model and estimate the 3D response of the whole valley. A research project, which is under progress, will contribute for this purpose; results are expected during the next two years.

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