Distribution of peak and spectral frequencies in Lisbon. Application of geological and geotechnical data

P. Teves-Costa
University of Lisbon, Instituto Dom Luiz & FCUL-DEGGE, Portugal

I.M. Almeida
University of Lisbon, Centre of Geology & FCUL-DG, Portugal

I.N. Rodrigues
University of Lisbon, Instituto Dom Luiz, Lisbon, Portugal

SUMMARY:
Due to its particular location and taking into consideration the historical records, the city of Lisbon is characterized by a moderate to high seismic risk. Estimating the impact of a future earthquake has been the interest of several researchers since many years. The seismic response of Lisbon is here presented, based on a combined analysis of geophysical and geotechnical data. Soil columns were defined, for a regular 250*250 m wide grid, from a 3D geological model obtained using a geological and geotechnical database. The physical parameters of each layer were estimated using empirical correlations from N_{SPT}. Two seismic scenarios were selected and theoretical transfer functions were estimated. Further adjustments to the shear-wave velocity of the soil layers were made using experimental H/V curves obtained from ambient vibrations measurements. The results are presented in terms of peak dominant frequencies and spectral amplification factors for 1 Hz and 2.5 Hz.

Keywords: Spectral amplification, Geotechnical data, Lisbon, Peak frequencies distribution, H/V

1. INTRODUCTION

Since historical times, Lisbon has been affected by several medium to strong earthquakes. The first well reported earthquake was the January 26th 1531 earthquake ($M \approx 7$) generated inland, in the Lower Tagus valley seismogenic area (Moreira, 1991), producing large damage in Lisbon (MM intensities of VIII and IX): about 25% of the houses were damaged, 10% totally collapsed and 2% of the population was killed (Henriques et al., 1988). Strong earthquakes with source offshore affected also Lisbon as the November 1st 1755 earthquake ($M \geq 8$), that caused considerable damage and killed many people, producing large economic and social impacts. Due to this moderate to high seismic risk of Lisbon, some studies were already developed in order to estimate the potential damage due to the occurrence of future earthquakes (Pais et al., 2001; Campos Costa et al., 2006; Carvalho et al., 2008; Oliveira, 2008; Teves-Costa and Barreira, 2012). However, in order to perform adequate damage estimation it is crucial to study the seismic behaviour of the surface layers, since it is well known their influence on the modification of the seismic ground motion characteristics.

In fact, several studies have shown the existence of resonance effects due to the natural vibration of the shallower soil layers and the fundamental period of the settled buildings (Chavez-Garcia and Cuenca, 1996; Chávez-García, 2007). This often results on unexpected higher levels of damage, which can increase by up to two degrees the intensity on the European Macroseismic Scale, EMS98 (Grunthal 1998).

This paper presents the geologic and geotechnical characterization of Lisbon's shallower formations, using the information compiled in a geoscientific information system developed in the aim of the GeoSIS_Lx Portuguese research project (http://geosislx.cm-lisboa.pt) (Almeida et al., 2010). This system also allowed the geological and geotechnical 3D modelling of the city (Matildes et al., 2010) which, in turns, enabled the definition of 1560 soil columns. From 1D theoretical seismic response of these columns it was possible to estimate the seismic behaviour of Lisbon in terms of peak frequencies and corresponding amplification factors, and spectral amplification factors for 1 Hz and 2.5 Hz.

2. GEOLOGICAL AND GEOTECHNICAL SETTING

2.1 Surface geology

The geological setting of Lisbon is characterized by a south-western area, landscaped in Mesozoic formations including Cretaceous marls and limestones and neo-Cretaceous basalts, associated with the evolution of the Lusitanian basin, and the eastern and north-western area, with Cenozoic formations, mainly Palaeocene and Miocene sedimentary series, associated with the genesis and evolution of the Lower Tagus river basin. During the Miocene, an open connection with the sea allowed the deposition of a complete estuarine sequence, with alternate marine and continental facies. The total thickness of the complete sequence can be as great as approximately 300 m. As the Miocene forms a monocline dipping east, the sequence is thinner in the west and thicker eastwards. Almost all the area is covered by Holocene materials including alluvium from Tagus River and tributaries streams, filling the main valleys, and artificial deposits associated to the urban evolution. The geological map of Lisbon is presented in Figure 1.

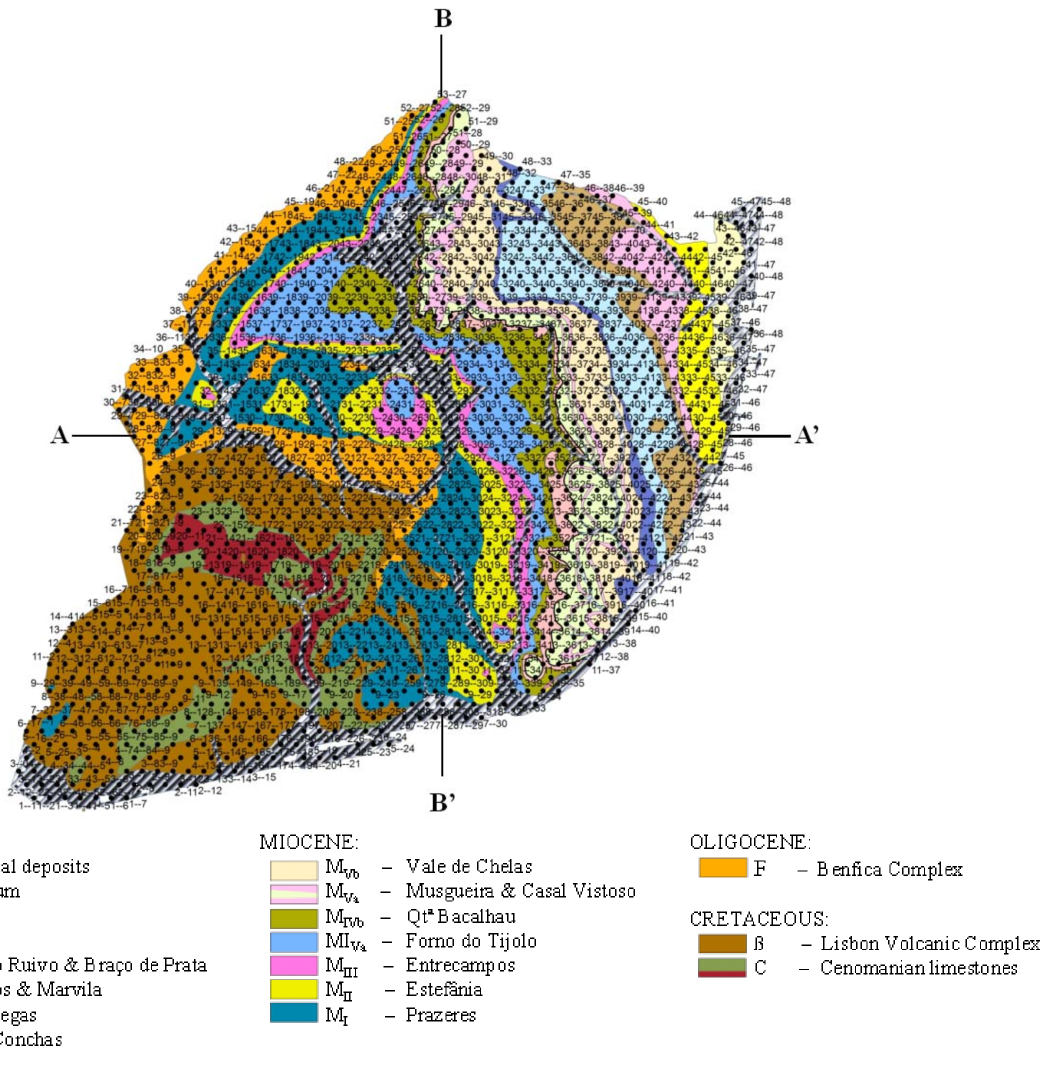

Figure 1. Geological map of Lisbon (adapted from Almeida, 1986) with the location of the soil profiles. Geological profiles A-A' and B-B' are displayed in Figure 2

2.2 Geotechnical characterization

The characterization of the various lithostratigraphic units was carried out considering the geologic and geotechnical information existing in the database. The selected data included a total of 597 reports, 4170 surveys and 31912 standard penetration tests (N_{SPT}).

For each unit statistical analysis of N_{SPT} data were performed taking into consideration the tests depth. First, second and third quartiles (Q1, Q2 and Q3) were computed. Tables 2.1 to 2.4 present these results.

Table 2.1 – Statistical analysis of N_{SPT} values for the surface units

Unit	Depth	N_{SPT} >60	N_{SPT} <30	Q1*	Q2*	Q3*
Artificial deposits (At)	<5m	5%	90%	6	10	17
max. thickness ≈50 m	5-10m	5%	87%	8	12	18
total tests = 5945	10-15m	6%	85%	9	14	21
	>15m	8%	69%	15	20	30
Alluvium (Al)	<5m	2%	93%	3	7	14
max. thickness ≈50 m	5-10m	8%	83%	2	7	14
total tests = 2765	10-15m	9%	78%	4	11	23
	15-20m	5%	84%	2	7	19
	>20m	3%	88%	4	8	17

* Excluding N_{SPT} > 60

Table 2.2 – Statistical analysis of N_{SPT} values for the limestone Miocene units

Unit	Depth	N_{SPT} >60	N_{SPT} <30	Q1	Q2	Q3
Casal Vistoso & Musgueira	<5m	44%	31%	25	49	164
(M_{Va})	5-10m	53%	23%	32	64	180
max. thickness ≈ 35 m	10-15m	62%	10%	43	69	138
total tests = 1578	15-20m	72%	7%	50	75	138
	>20m	83%	4%	62	120	180
Qt Conchas (M_{Vc})	<5m	43%	45%	19	39	120
max. thickness ≈ 12 m	5-10m	55%	32%	27	72	150
total tests = 312	>10m	74%	5%	60	86	129
Entrecampos (M_{III})	<5m	49%	27%	29	60	129
max. thickness ≈ 17 m	5-10m	73%	11%	59	120	180
total tests = 398	10-15m	90%	6%	109	150	219
	>15m	90%	4%	105	180	225

Table 2.3 – Statistical analysis of N_{SPT} values for the clayed Miocene units

Unit	Depth	N_{SPT} >60	N_{SPT} <30	Q1	Q2	Q3
Xabregas (M_{VIa})	<5m	11%	70%	15	20	34
max. thickness ≈ 22 m	5-10m	25%	47%	20	32	60
total tests = 1187	10-15m	48%	21%	33	57	86
	15-20m	48%	20%	36	58	100
	>20m	70%	9%	52	64	108
Forno do Tijolo (M_{IVa})	<5m	22%	53%	18	29	54
max. thickness ≈ 40 m	5-10m	49%	26%	28	60	120
total tests = 2202	10-15m	61%	8%	46	67	129
	15-20m	76%	0%	60	67	120
	>20m	86%	2%	69	95	150
Prazeres (M_I)	<5m	19%	59%	13	24	49
max. thickness ≈ 35 m	5-10m	40%	30%	34	62	120
total tests = 5653	10-15m	64%	10%	45	72	138
	15-20m	67%	7%	51	69	129
	>20m	75%	5%	60	90	129

Table 2.4 – Statistical analysis of N_{SPT} values for the sandy Miocene units

Unit	Depth	N_{SPT} >60	N_{SPT} <30	Q1	Q2	Q3
Cabo Ruivo + Braço de Prata						
(M_{VII})	<5m	23%	59%	18	26	51
max. thickness ≈ 42 m	5-10m	31%	36%	26	37	72
total tests = 3427	10-15m	47%	17%	34	54	120
	15-20m	61%	7%	45	64	138
	>20m	67%	6%	51	72	180
Vale de Chelas (M_{Vb})	<5m	27%	51%	17	30	64
max. thickness ≈ 35 m	5-10m	56%	24%	32	67	129
total tests = 1300	10-15m	76%	11%	60	90	157
	>15m	81%	7%	103	164	360
Qt Bacalhau (M_{IVb})	<5m	8%	69%	13	21	35
max. thickness ≈ 35 m	5-10m	33%	30%	27	44	72
total tests = 1079	10-15m	58%	11%	44	62	106
	15-20m	71%	6%	53	69	103
	>20m	90%	2%	72	90	120
Estefânia (M_{II})	<5m	24%	48%	19	32	60
max. thickness ≈ 36 m	5-10m	39%	33%	25	43	95
total tests = 2533	10-15m	49%	20%	34	57	120
	15-20m	56%	18%	36	64	120
	>20m	75%	5%	60	88	150

2.3 Geological and geotechnical modelling

The geological and geotechnical 3D modelling of the city (Matildes et al., 2010) enabled the rough definition of any geological profiles. Figure 2 presents, as example, a north-south and a west-east geological profiles which locations are indicated in Figure 1.

From a set of similar profiles, it was possible to define detailed soil columns. Using a regular grid of 250*250 m wide to cover whole the area (see Figure 1), 1560 soil columns were selected. Each column is characterized by the thickness of infill and the sequence of the different geological layers characterized by their lithology and thickness. Whenever possible the procedure was controlled by local borehole information.

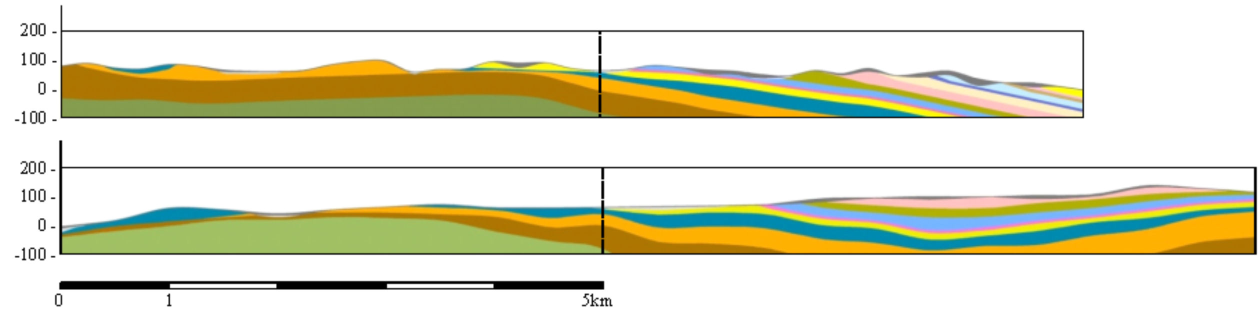

Figure 2. Top: geological west-east (A-A') profile. Bottom: geological north-south (B-B') profile (see location and legend on Figure 1)

The shear wave velocity of each layer was estimated using empirical correlations, with N_{SPT} values, available in the bibliography, Eqn 2.1 (Imai, 1977; Imai and Tonouchi, 1982; Lee, 1990; Jafari et al., 1997; Dikmen, 2009; etc.). Several empirical relations were applied and, using the H/V curve for calibration (see next sections), the selected expressions for the different lithologies are presented in Table 2.5.

At 25 m or deeper the shear wave velocity was assumed constant and equal to 900 m/s for the Miocene formations. The older formations (Oligocene and Cretaceous) behave like rock and were considered bedrock with shear wave velocity larger than 1000 m/s, according to information collected in the bibliography. However, for the first 5 m the empirical relationships were still used because these formations are often superficially unloaded.

The specific weight for the surface materials, ρ (kN/m3), were estimated using Eqn. 2.2 from (Bowles 1982). For the other geological formations we assumed a mean value taking into consideration their lithological composition.

$$V_S = \alpha\, N_{SPT}^{\beta} \tag{2.1}$$

$$\rho = 2 \ln (N_{SPT}) + 12.1 \quad \text{(for alluvium)} \tag{2.2}$$
$$\rho = 2.1 \ln (N_{SPT}) + 11 \quad \text{(for artificial deposits)}$$

Table 2.5 – α and β values used in Eqn 2.1 and specific weight (ρ) for the different geological formations

Unit	α	β	ρ	Reference
Artificial deposits	58.0	0.39	15.4	Dikmen (2009)
Alluvium	58.0	0.39	17	Dikmen (2009)
Miocene:				
Sand	56.0	0.49		Lee (1990)
Clay	76.6	0.45	21.0	Athanasopoulos (1995)
Limestone	76.6	0.45		Athanasopoulos (1995)
Rock	22.0	0.85	22.0	Jafari et al (1997)

3. SOIL CHARACTERIZATION USING H/V CURVES

In order to characterize the different soil columns, in terms of natural frequency and predominant frequency, a set of ambient vibrations were performed using a LEAS Cityshark seismic station with a Lennartz LE3D 5s seismometer. The objective was not to acquire records on the top of every soil column, but to sample the different geological formations present in the city. About 50 sites were selected scattered through Lisbon. Data processing was performed using Geopsy software (http://www.geopsy.org/index.html) to obtain the H/V curve (Nakamura, 1989). Figure 3 presents, as example, three H/V curves obtained on different geological formations. As expected, the H/V curve obtained on the rock formation (Lisbon Volcanic Complex) does not exhibit frequency peak.

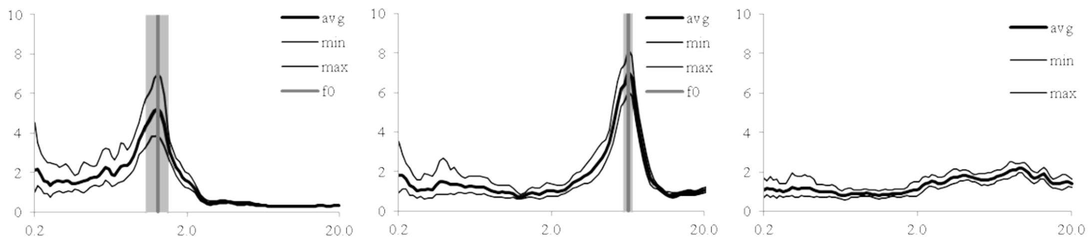

Figure 3. H/V curves obtained on different geological formations. From left to right: alluvium, Miocene clay and bedrock (Lisbon Volcanic Complex)

The obtained H/V curves were used to calibrate the shear wave velocity estimation of the different layers by comparison with theoretical transfer function, as explained in the next section.

4. THEORETICAL TRANSFER FUNCTIONS

To estimate the seismic behaviour of the different soil columns, theoretical transfer functions were computed using the linear equivalent method (ProShake; Schnabel et al., 1972). Taking into account the historical and instrumental seismicity of Lisbon, two seismic scenarios were selected to define the input motion: a near source M=6.0 at D=25 km and a far source M=7.9 at D=250 km. These scenarios are in agreement with the seismic actions present in the Portuguese National Annex of Eurocode 8 (IPQ, 2010). A set of synthetic accelerograms, for each scenario, was computed using Berge-Thierry et al. (2003) and Pousse et al. (2006) approximations (Figure 4).

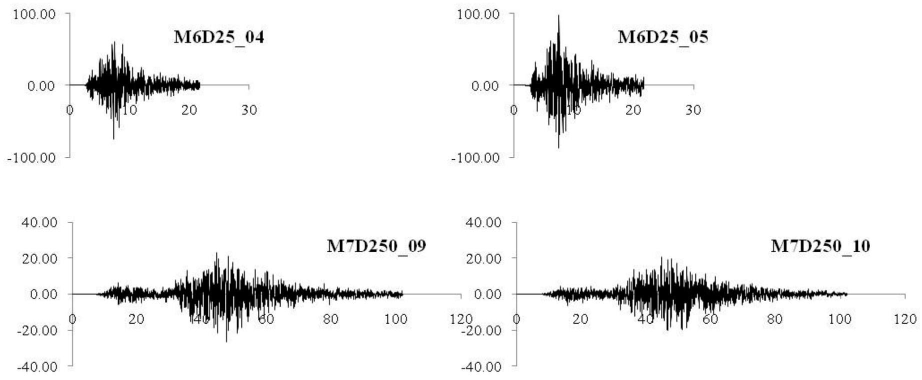

Figure 4. Synthetic accelerograms used to simulate input motions (near – top; far - bottom).

To constraint the shear-wave velocity of the shallower formations the H/V curves computed from ambient vibrations were used. Comparing the natural frequency (F0) of the theoretical transfer functions with the peak frequency of the experimental H/V curve it was possible to adjust the shear-wave velocity of the soil layers. With this procedure, which is illustrated in Figure 5, it was possible to choose the most adequate empirical relations for each lithological formation (Teves-Costa et al., 2010) (see Table 2.2).

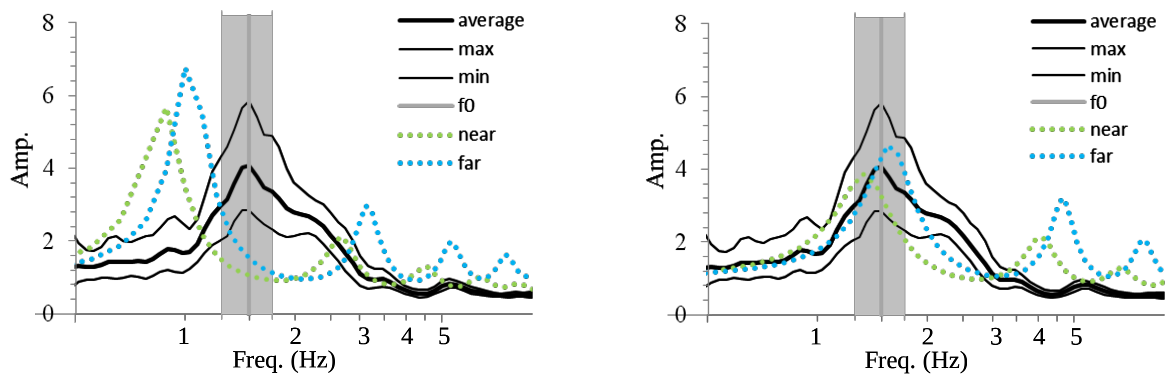

Figure 5. Shear wave velocity estimation by comparing the H/V curves (in black) with the theoretical transfer functions (green and blue curves). Left: initial Vs values; Right: final Vs values

After defining the physical parameters for all soil columns (lithological layer sequence and corresponding thickness, density and shear wave velocity, down to the bedrock) theoretical transfer functions were computed for all 1560 soil columns. For simplicity the results are presented only for one input motion corresponding to each source (near and far sources). Differences among the results obtained with the different accelerograms for the same input motion are not relevant.

5. SEISMIC RESPONSE MAPS

From the analysis of the computed transfer functions it is possible to observe the seismic response of Lisbon. The results are presented as contour maps for the two input motions in terms of dominant frequencies and corresponding amplification factors (Figure 6 and 7), and in terms of spectral amplification factors for 1 Hz and 2.5 Hz (Figures 8 and 9). The presentation in terms of dominant (or peak) frequency is appropriate because the soil ground motion will be more amplified close to these frequencies. The selection of 1Hz and 2.5 Hz to present the spectral response was done due to the natural frequencies of most buildings in Lisbon with 8 or more stories (Oliveira, 2004). The particular downtown building stock, constructed with seismic resistance techniques after the 1755 earthquake, has natural frequencies between 2.3 and 3 Hz (Oliveira, 2004).

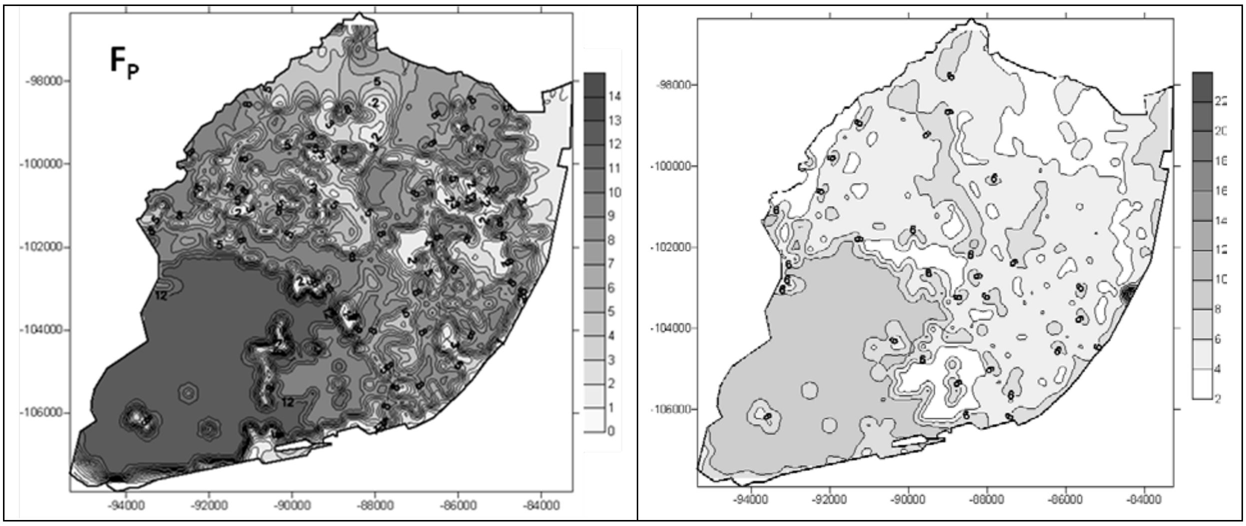

Figure 6. Predominant frequencies (F_P) (left) and corresponding amplification factors (right) – for near motion.

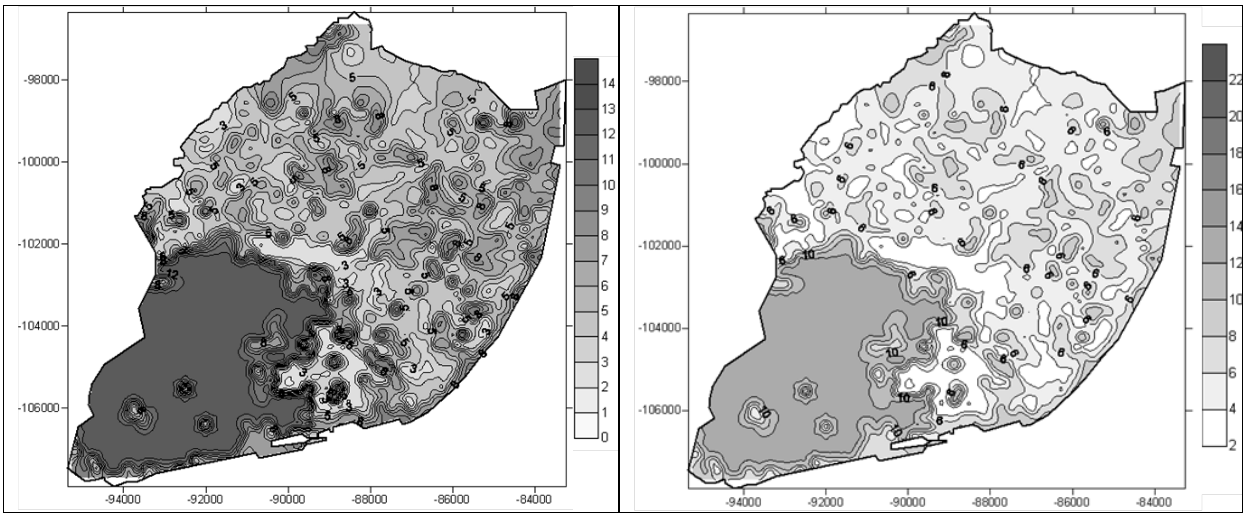

Figure 7. Predominant frequencies (F_P) (left) and corresponding amplification factors (right) – for far motion.

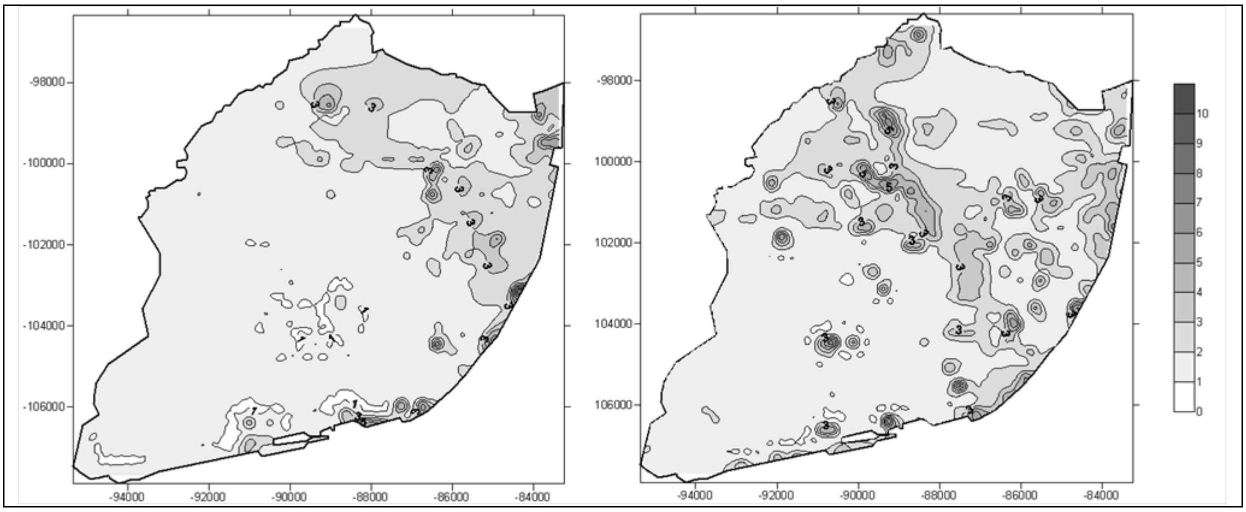

Figure 8. Amplification factors for F= 1Hz (left) and for F= 2.5Hz (right) – for near motion.

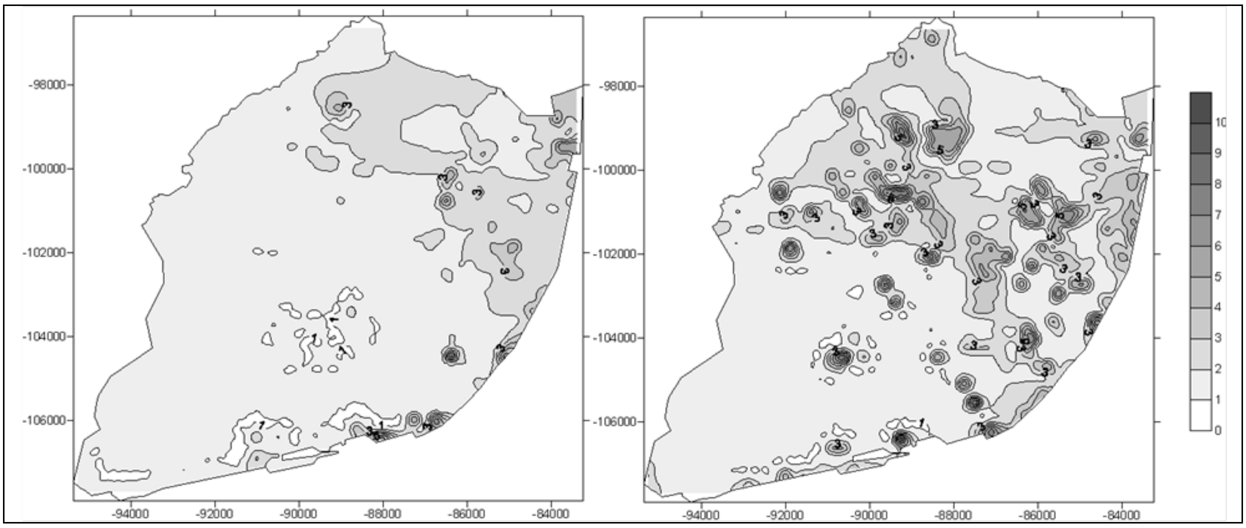

Figure 9. Amplification factors for F= 1Hz (left) and F= 2.5Hz (right) – for far motion.

From the analysis of Figures 6 and 7 it is clear that the predominant frequency of Lisbon is, on average, close to 5 Hz, except for the south west zone of the city where the Lisbon Volcanic Complex and the Cenomanian limestone outcrops (as already referred, over these rock formations it is not possible to define a predominant frequency). We can say that the predominant frequency may vary between 3 and 8 Hz, depending on local geology and the morphology; the motion associated with these predominant frequencies may be amplified up to 4 times on average, reaching a factor 6 in some particular sites. No relevant differences for the two input motions are observed.

Figure 8 shows that the amplification of the seismic motion close to 1 Hz is very small (1 or 2), rarely reaching 3. For the seismic motion close to 2.5 Hz, the amplification is slightly higher, up to 3 or 5 at some particular sites (Figure 9). Again, no relevant differences can be observed for the two input motions

6. CONCLUSIONS

This paper presented a geological and geotechnical characterization of the different geological units of Lisbon. Using the integrated information of the Geotechnical Database, the 3D geological modelling and geotechnical characterization, it was possible to define and assign physical properties of a regular grid of 1560 soil columns.

The theoretical modelling of the seismic behaviour of these columns allowed drawing maps of dominant frequencies for the city, as well as maps of ground motion amplification for certain frequencies. The analysis of these maps enabled the identification of the distribution of dominant frequencies along the city, exhibiting a good correlation with the local geology and the morphology: the dominant frequency of Lisbon is, on average, close to 5 Hz, varying between 3 and 8 Hz; in rock regions, where Cretaceous formations outcrop, it is not possible to define a dominant frequency; in the depressed alluvial areas, this frequency can be lower, close to 2 Hz, as seen in the downtown area (Teves-Costa et al., 2010); the amplification factor of the dominant frequency can be equal to or greater than 4, showing the need to pay attention to the building's natural frequencies.

Finally the amplification of the seismic motion for two particular frequencies (1 Hz and 2.5 Hz) was also analysed allowing the following conclusions: there is no relevant amplification for the ground motion at 1Hz; but for 2.5 Hz, the seismic motion can be amplified to about 3 times, and in some particular points, up to 5 times.

Given the complexity of the geological model and the difficulty in defining parameters for the whole Lisbon area, the obtained results were dependent on the quantity and quality of the existing information. The use of a regular grid has advantages in the geographic modelling but does not take into account particular situations as for example deep artificial deposits associated to abandoned quarries or marginal reclaimed land. These cases should be considered in further analysis.

Although these results present an important development in relation to previous works, it is evident the need for further studies involving geophysical techniques to allow a direct validation of the estimated parameters. However, it is also evident the need to take into consideration the building natural frequency and its construction site. Local amplification may occur for certain frequencies of the seismic motion.

This type of study developed for a large town exhibiting moderate to high seismic risk could be of great importance for the assessment of the impact of a future earthquake, in terms of damage estimation, and for emergency planning and prevention measures.

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