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GEOTECHNICAL CHARACTERIZATION IN LISBON AND SURROUNDING COUNTIES FOR EARTHQUAKE ENGINEERING PROPOSES

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SUMMARY

The geotechnical soil characterization of the Lisbon Metropolitan Area and Adjacent Counties was based on the analysis of data obtained from geotechnical boreholes, geophysical methods, and laboratory analysis. In order to characterize their seismic behaviour, the soils in this area were classified in 4 different classes. Linear modelling was performed for all soil types, and non-linear modelling for the most vulnerable soil type. The most vulnerable situations were identified, corresponding, in practice, to an increase of 1 or 2 degrees in the observed seismic intensity.

INTRODUCTION

Through its history, Portugal mainland has experienced the effects of various moderate to strong earthquakes, thus presenting a moderate seismic risk, more important in the Lisbon and Lower Tagus Valley, and Algarve regions. In consequence, the National Civil Protection Service promoted a study of the seismic risk in the Lisbon metropolitan area and adjacent counties, involving technicians and researchers from various institutions. In the adopted methodology, the parish was considered as the analysis unit, and the location of the Parish Board representative of the total parish.

The geotechnical soil characterization is of the utmost importance for seismic risk assessment, being used, in particular, for site effect assessment. Those effects may be defined as phenomena originating significant changes in the seismic movement in a given location, increasing the seismic intensity observed by 1 or 2 degrees. They depend mainly on the geological, geotechnical and topographic site characteristics.

The methodology used for soil characterization in the area under study is presented in this work, as well as some of the results, which emphasize the amplification potential of the seismic movement at the surface under certain conditions, for a few soil types.

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GEOLOGICAL SETING

The area studied is located in the Lusitanian Basin, which developed since the Triassic, in relation with the North Atlantic opening. The Lusitanian Basin has a maximum depth of meso-cenozoic sediments of approximately 4 km, extending onshore for approximately 320 km N-S and 180 km E-W, with a considerable offshore extension [1]. The contact area with the westerly basin edge, partially covered by sediments from the Tagus river basin, is constituted by rocks from the Hesperic Massif (Figure 1).

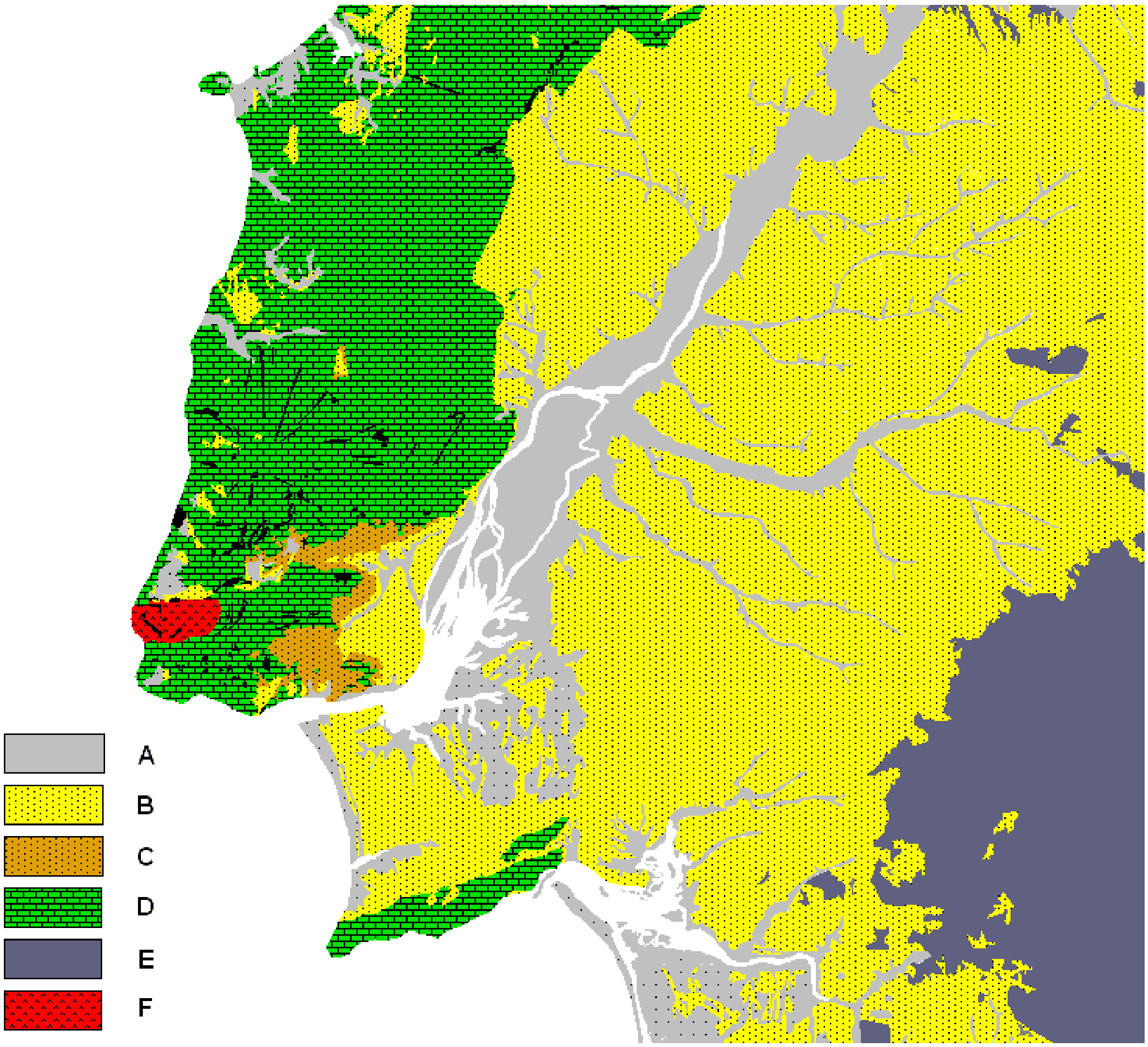


Figure 1: Geological setting of the studied area: A – alluvium (Holocene); B – Mio-Pleistocene; C – Lisbon Volcanic Complex, D – Mesozoic; E – Hercynian basement (Pre-Mesozoic Hesperic Massif); F – Sintra Eruptive Massif.

The morphology of the actual Tagus river valley was excavated approximately 18,000 years ago, when the water level was approximately 120 m below the actual level, excavating not only the Plio-Pleistocene formations but also the Miocene bedrock.

The formation genesis and evolution have contributed to different mechanical behaviours. The Mesozoic formations, which were subject to an intense diagenesis process, including particle cementation, are predominantly constituted by rocks, including limestone, sandstone, and clay. The Tertiary formations, with lower diagenetic evolution, but having been submitted to an intense over-consolidation process, are predominantly constituted by hard soils and soft rocks. The Quaternary formations, predominantly constituted by normally consolidated or lightly over-consolidated soils, include very soft to hard clays and very loose to dense sands, depending upon the compaction and consolidation processes.

GEOLOGICAL AND GEOTECHNICAL SOIL CHARACTERIZATION

To evaluate the site effects associated with the local geological and geotechnical conditions, it is necessary to know the sequence of the geological layers, including depth, lithological and geotechnical characterization. That information can be obtained by geological-geotechnical borehole, identifying and characterizing the soil column, and performing *"in situ"* or laboratory tests. However, borehole data is only representative of local conditions, and their extrapolation must be carefully evaluated.

In the case of the Lisbon Metropolitan Area (AML) and Adjacent Counties, where the working area is vast and geological conditions vary considerably, it is impossible to consider the existence of boreholes in sufficient number and geographical distribution to allow characterization of the full working area. Among the different available means to overcome this gap, it was considered the information contained in geologic maps published at the 1:50,000 scale which, even with a relatively small scale and an essentially stratigraphic character, allows qualitative reconstruction of local geological and geotechnical conditions, taking into account the geological history associated to the stratigraphic unit and the knowledge of some material properties.

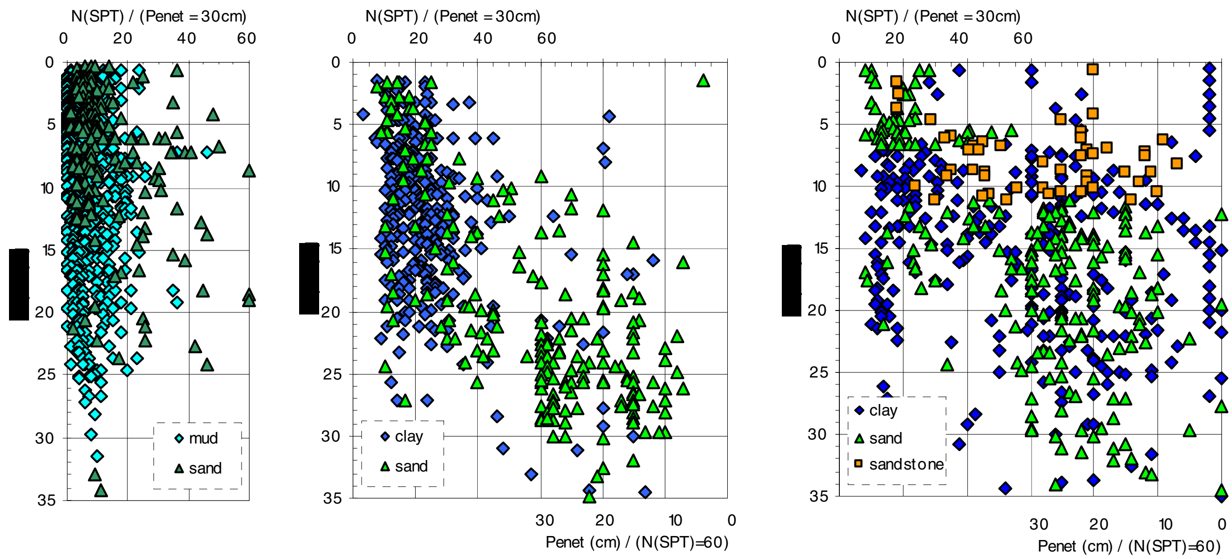
Having considered the parish as the unit and the Parish Board location in first place, it was tried to identify and, as much as possible quantify, the different existing situations. To each parish it was then associated up to five different geological conditions, considering, in first place, the situation corresponding to the parish location, followed by its representativeness, in decreasing sequence, in the total parish, including the geological sequence, estimating, from the respective Explanatory Notes, the maximum thickness value of local geological units.

Given the extension of the area under study, the variability of the spatial distribution of the geotechnical characteristics of the different geological/geotechnical units and the reduced existing information volume, the geotechnical characterization of the surface soils must be considered as a semi-quantitative approach. The main lithostratigraphic units have been considered, grouping adjacent units with similar behaviour, or in wider groups, when area dimension does not justify sub-divisions.

The information contained in the consulted reports is very much incomplete in the majority of the cases, requiring a first phase interpretation and systematisation. During borehole data treatment, particular attention was given to the results of SPT tests, not only because they allow evaluation of the main characteristics of the intersected soils, but also because of data relative frequency. In the statistic treatment, it was considered for each unit the main present lithologies and several depth intervals (Figure 2). In the case of over-consolidated soils, with soft rock intercalations, N(SPT) values are very high, changing the meaning of some statistical parameters, such as median and standard deviation. For that reason it was considered that the median should be chosen as the most significant parameter.

Taking into account the set of data collected, it was tried to treat data considering their characterization by geographical areas, grouped in the following zones: A1 (Lisbon-Aveiras); VFX (Vila Franca de Xira); A9-CREL (National Stadium-Alverca); Lisbon (Lisbon County); A2 + A12 (Setúbal Peninsula). Treatment of existing information has allowed definition of main existing soil characteristics in each zone (Tables 1 and 2).

As it can be observed in Table 2, the main units corresponds to recent surficial deposits (Surf. dep) and talus (Talus), corresponding to materials with different compaction ratios, alluvial deposits from the Lower Tagus Basin (Al. Tagus) or from secondary rivers (Alluvium) with normally consolidated soils, Quaternary terraces deposits from the Tagus (Terraces) with gravely and hard soils and Pliocene and Miocene deposits with overconsolidated soils superficially decompressed.



(a) **(b)** **(c)**

Figure 2: N(SPT) distribution with depth and with lithology in the Vila Franca de Xira zone (VFX), corresponding to values presented in tables 1 and 2: (a) Alluvium; (b) Pliocene; (c) Miocene.

Table 1: Quantification of data collected from the various zones.

	A1	VFX	A9	Lisbon	A2 + A12
Nº sound	88	184	98	1804	179
Nº SPT	940	2448	246	16052	1743
Nº samples	173	---	90	---	219

Table 2: Evolution of the SPT test median values with depth analysed for the various zones. Values between brackets correspond to higher depth.

	A1	VFX	A9	Lisbon	A2 + A12
Surf. dep.	9 (16)	10	---	15	---
Al. Tagus	4 (7)	4 (9)	---	4 (9)	
Alluvium	---	---	---	13	13
Talus		28 (>60)	37	---	---
Terraces	36 (60) (>60)		---	---	---
Pliocene		18 (>60)	---	---	28 (48)
Miocene	60 (>60)	39 (60) (>60)	---	>20 (>60)	26 (>30)

Soil classification

As it's common knowledge, soil conditions affect signal at the surface. It may be said that the signal does not experience large changes since its generation until a rocky place, except those inherent to energy fading with distance, assuming that the medium does not present large heterogeneities. However, local conditions may cause signal modifications in such way as to cause an increase of 1 or 2 degrees in the observed seismic intensity. For that reason, it is necessary to perform soil classification, grouping in two or more categories.

In the RSA document (Safety Regulations and Actions for Buildings and Bridge Structures) still in use in Portugal, soils are classified in 3 simple categories: I – rocks and hard coherent soils; II – very hard coherent soils; hard and of medium consistency; compact incoherent soils; III – soft and very soft coherent soils; loose incoherent soils. On the other hand, in the Eurocode 8 (EC8), soon to come in effect, 3 soil categories are also presented, but their description is a lot more detailed and based on cross wave propagation velocity.

In the specific case of AML and Adjacent Counties, it was decided to use a simple classification, based mainly on surface geology and lithology, dividing soils in 4 distinct categories:

1 – Rock formations from Jurassic, Cretaceous, Lisbon Volcanic Complex and Sintra Eruptive Massif;

2 – Formations of more or less resistant rocks and hard soils (limestone, clays and conglomerate) from the Oligocene and Miocene;

3 – Predominantly sandy formations from the Miocene, Pliocene and Quaternary deposits;

4 – Alluviums, dune sands and surface sands.

DETERMINATION OF TRANSFER FUNCTIONS

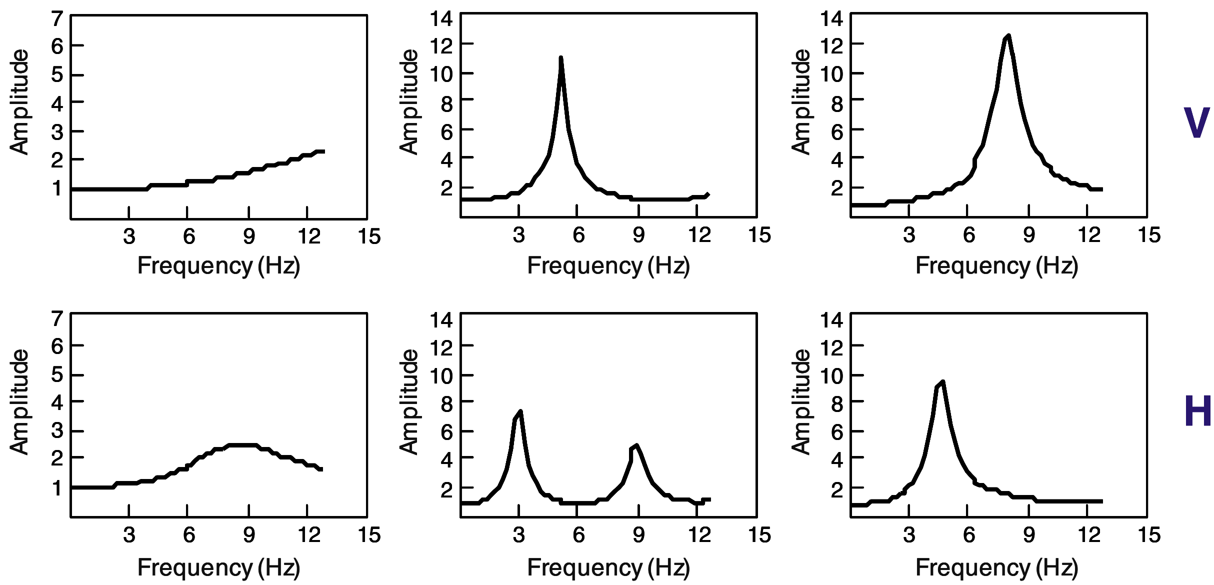
Site effects may be estimated in a theoretical way, by the response of a soil column to an input motion. It is possible to compute the surface motion by introducing a real seismic signal at the base of the column. It is usual to introduce a signal (an accelerogram) corresponding to a past event, preferably registered on rock and close to the site under study. It is also possible to calculate the response to a unitary signal, thus obtaining the transfer function for the soil column. The column response depends on the physical characteristics of the constituting materials, particularly thickness, density, shear wave velocity, and damping coeficient for each layer. Mathematical modelling of soil response to seismic inputs can be performed assuming elastic and linear properties, or considering non-linear soil behaviour (which leads to a more realist result). Nevertheless, linear modelling continues to be often used, since it gives a quick estimate of soil behaviour, emphasizing eventual differences among different soil columns. Besides, non-linear behaviour may be approximated through an iterative series of linear calculations, using an equivalent viscoelastic model for the soil.

Linear approach

Mathematical modelling consisted in the application of the unidimentional method of Thomson-Haskell [2], considering vertically incident P and SH waves. This method may be used when the structure is approximately horizontally stratified, and it supplies the natural frequency and the approximate value of maximum amplification of the soil movement in two directions (horizontal component, H, and vertical component, V). To apply it, it is necessary to define a unidimentional structure, consisting on a set of overlapping layers with different depths and attribute to each layer a density, seismic waves propagation velocities and quality factor, for P and S waves.

The depths of the different layers were obtained from the geological characterization referred in the previous paragraph, considering the Parish Board location. The density was estimated taking into account the lithological composition and depth of each geological formation. Seismic wave velocities were estimated not only from SPT values, but also considering the values obtained from the geophysical prospection tests, from [3], and from data published in specialized literature; whenever necessary, the value of 0.25 was used for Poisson coefficient, to estimate propagation velocity of P from S waves, or vice-versa. Finally, the quality factor of the different layers was estimated, taking into account the lithological composition, layer depth, and type of incident wave.

A soil column was defined for each Parish Board location, in accordance with the described methodology. Transfer functions were calculated for horizontal and vertical soil movements, for all Parish Boards not settled on rock. In total, transfer functions for 166 soil columns were calculated. It must be observed that maximum depths for surface deposits were considered. This hipothesys corresponds to an extreme situation and, in consequence, may not represent the real situation for the majority of parishes in question. As an example, transfer functions for three different parishes of the Lisbon County are presented in figure 3.



(a) **(b)** **(c)**

Figure 3: Transfer functions for vertical and horizontal movements, for Alvalade (a), S. Paulo (b) and Santa Maria de Belém (c) parishes. Alvalade is settled over 50 m of limestones and calcareous sandstones (Vs = 440-1200 m/s), superimposed on 30 m of silty fine sands (Vs = 300 m/s) laying over a substractum composed by silty clays interlayered with limestones (Vs = 1200 m/s); S. Paulo presents 10 m of alluvium (Vs = 120 m/s), superimposed on 30 m of silty clays interlayered with limestones (Vs = 650 – 1200 m/s) laying over a basalt bedrock (Vs = 1900 m/s); Santa Maria de Belém presents 15 m of alluvium (Vs = 120-150 m/s), superimposed on 100 m of basalt (Vs = 1900 m/s), laying over a Cretaceous bedrock composed by limestones (Vs = 1900 m/s).

It may be observed from figure 3 that the alluvium layers show an important role. The other main parameter is the seismic impedance contrast between the surface layers and the substractum.

In an attempt to identify differences on the seismic behaviour for the various soil types, an analysis of the peak values of the transfer functions previously calculated was performed, in terms of amplitudes and frequencies, for both components of the soil movement. Parishes were grouped in accordance with the soil classification presented before, and graphs were drawn showing the variation, in amplitude and frequency, of calculated transfer functions, for each soil type. Figure 4 synthesises the obtained results, in terms of maximum spectral amplitude, for all parishes studied.

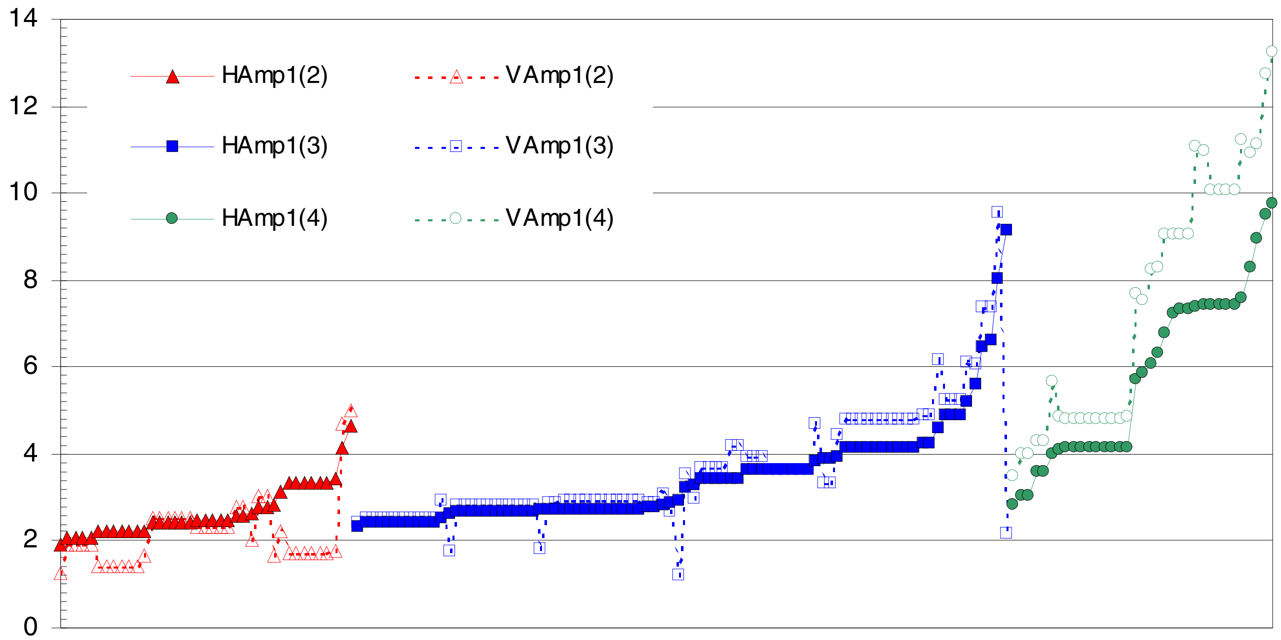


Figure 4: Synthesis of peak amplitudes calculated for horizontal and vertical movements, for all parishes, grouped by soil type, and represented by increasing values of horizontal movement amplitude. On the left are represented the parishes with soil type 2, on the center, parishes with soil type 3 and, on the right, parishes with soil type 4.

These graphs permit to observe that, on soil type 2, for example, the amplifications for both horizontal and vertical movements, are below 4; on soils type 3, the amplifications varies between 2 and 5; and, in the case of soils type 4, the amplifications are up to almost 10 for the horizontal movement, and 13 for the vertical movement. The same type of analysis could have been performed for the peak frequencies.
However, even of greater importance, this type of analysis has enabled the detection of a few anomalous situations, by identifying parishes which did not present the same behaviour as others with the same type of soil. One of those anomalies can be observed on the central part of Figure 4 where some parishes show amplifications of much greater level than others. Looking in detail for the geological situation of those anomalous points, we concluded that the Quaternary and some Pliocenic formations, when superimposed on soils type 1 or 2, present a type 4 soil behaviour. That is, in the cases where there is a large seismic impedance contrast, the amplification of the soil movement may be larger than initially forseen. This constitutes an important observation for the estimating of the surface seismic motion.

Non-linear approach

According to the previous analysis, it was verified that, with a few exceptions, the zones more prone to present a less favorable seismic behaviour are those with soils type 4. With the objective of trying to characterize in detail the seismic behaviour of those soils, a mathematical modelling to estimate transfer functions was performed, using a non-linear approach. To apply that methodology, an area close to the Tagus river was selected, since there was detailed information on the first meters of soil, deriving from geotechnical boreholes (figure 5).

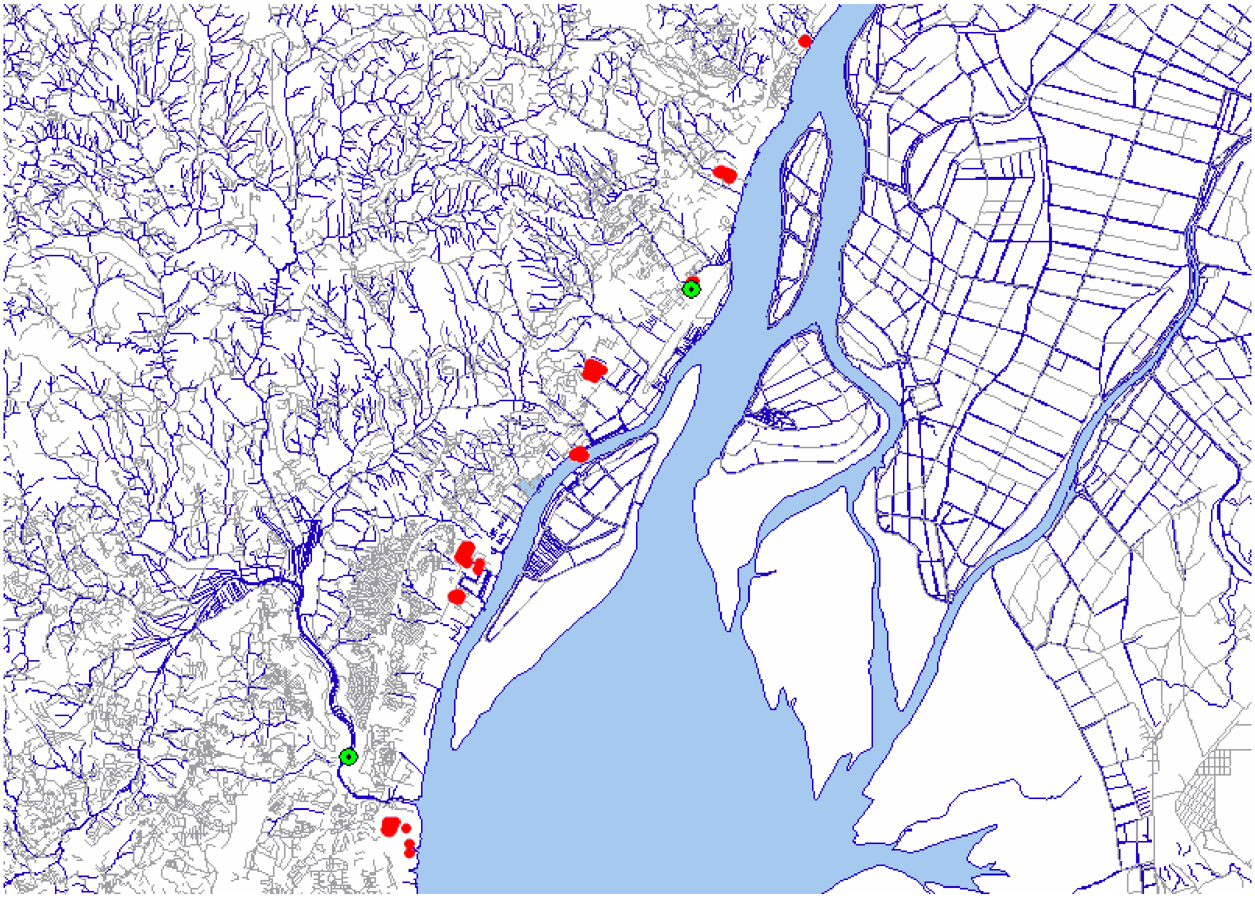


Figure 5: Boreholes locations in the Póvoa de Santa Iria area. The boreholes presented in green correspond to those selected for mathematical modelling.

The SHAKE program, developed to perform one-dimensional linear equivalent ground response analysys, was used to estimate the transfer functions for several soil columns, selected in accordance with the various situations presented. The thicknesses of the different units were retrieved directly from the soundings, and the velocities and specific weights estimated from empiric relations selected from the literature [4] and laboratory data analysis [5].

In Figure 6 we present, for comparison the results from the mathematical computations for two selected boreholes located in the Unhos parish (upper curves) and the Santa Iria parish (lower graphs). For each borehole two transfer functions were determined: one from the non-linear approach using the linear equivalent method (graphs (a) and (d) on the left), and other from a linear approach with damping (graphs (b) and (e) on the middle). We computed also the linear approach with damping for the soil columns corresponding to both parish boards (graphs (c) and (f) on the right). For both parishes, comparing the non-linear with the linear with damping approaches, we can see that the non-linear approach give smaller amplitude levels for the transfer functions, and shift the peak amplitude for a lower frequency. Comparing the two linear with damping approaches we can see that in the same parish we can different soil responses corresponding to different geotechnical situations. To have a result closer to the real situations, we must take the dominant soil of the parish (i.e., the soil that covered the biggest area) and we must look with more care to the urban zones inside each parish.

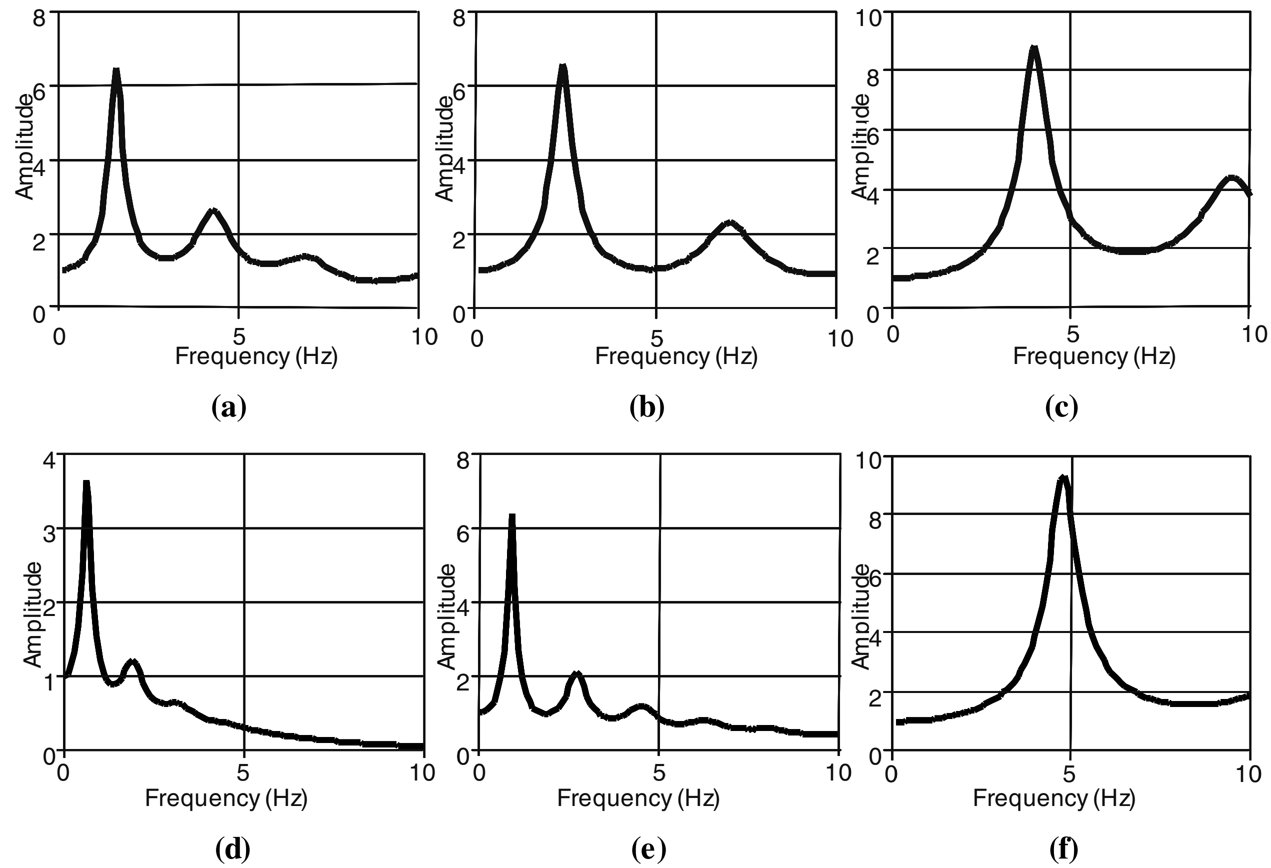


Figure 6: Transfer functions of 2 soil columns located in the Unhos parish (upper graphs) and Póvoa de Santa Iria parish (lower graphs). The column of the Unhos parish is composed by 10 m of surficial fill (Vs = 170 m/s), superimposed to 8.3 m of mud (Vs = 199 m/s), 0.55 m of marly sandstone (C), 1.98 m of marble (Vs = 450 m/s), laying on a miocenic substractum (Vs = 700 m/s); and the column of Póvoa de Santa Iria parish is composed by 28 m of silty mud (Vs = 102 m/s), superimposed to 2.5 m of clayed sandstone (Vs = 390 m/s), laying on the same type of substractum (Vs = 700 m/s). Graphs on the left, (a) and (d), present the transfer function from the non-linear approach determined with the linear equivalent method; graphs on the middle, (b) and (e), present the transfer function obtained from a linear approach with damping; graphs on the right, (c) and (f), present the transfer functions for the parish boards columns obtained from a linear approach with damping.

As shown, the soil type 4 is prone to amplify the seismic movement but there are not always important structures built on it. As an example, on the large alluvium thicknesses in Vila Franca de Xira, close to the Tagus river, there are no built-up structures which may suffer damages in case of an earthquake. This fact does not make this study less important, since it is not known if this kind of situation may exist somewhere else.

CONCLUSIONS

The geotechnical soil characterization in the Lisbon Metropolitan area and adjacent Counties was performed based on the analysis of data retrieved from geotechnical soundings, and laboratory analysis. With the objective of characterizing the seismic soil behaviour in this area, soils were classified in 4 distinct classes, one of them being “rock”. Linear modelling was performed for all soil types, noting that, depending on the surface soil type, thickness of the different layers, and type of bedrock present, large amplifications could be obtained for certain frequency values. However, it must be taken into account that maximum thicknesses for surface deposits were used, which corresponds to an extreme situation, which may, in consequence, not correspond to the real situation in the majority of the zones in question. On the other hand, since modelling was only referred to the Parish Board location, it may happen that more serious situations may be present in this region, which has not been contemplated in these approaches. This problem may only be overcome through detailed studies, which could be performed individually, for example, for each of the Counties.

Notwithstanding those limitations, soil types and particular situations more susceptible to amplify seismic movement were identified. For soil type 4, the non-linear unidimentional transfer function was computed for 2 different situations, emphasizing the potential amplification of the surface motion in these cases. In practice, this amplification may correspond to an increase of 1 to 2 degrees in the seismic intensity.

Finally, it is emphasized the “macroscopic” character of this study, for which reason it should not be extrapolated to a larger scale. To estimate site effects at an urban scale, for example, detailed studies should be performed, possibly following a methodology similar to the one adopted in this sudy.

ACKNOWLEDGEMENTS

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