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One-dimensional geotechnical modelling by seismic methods of Lisbon alluvial basins

Modélisation géotechnique unidimensionnelle de bassins alluvionnaires de Lisbonne par des méthodes sismiques

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ABSTRACT: An experimental seismic microzonation was executed in Lisbon, in 1991. In this paper the results obtained in alluvial basins are compared, by spectral analysis, with those from one-dimensional (1D) nonlinear models. Geotechnical parameters are estimated for some sites in each basin, such as layer thickness, soil type (clay, sand or rock), mass density and shear wave velocity. SHAKE program, with 1969/2/28 Lisbon's earthquake accelerogram, was used to optimize theoretic models. Average relationships between dynamic shear modulus and damping ratios of soils, as functions of shear strain, were considered.

With this analysis it was possible to verify the existence of great soil amplifications at low frequencies depending on alluvium thickness at each site.

RESUMÉ: Cet article présente la comparaison des résultats expérimentaux à partir d'un zonage sismique réalisé en 1991 et des résultats théoriques obtenus par des modèles unidimensionnels non-linéaires de l'analyse spectral. Des paramètres géotechniques sont estimés en plusieurs points de chaque bassin, notamment: épaisseur des couches, nature du sol (argile, sable et roche) poids spécifique et vitesse des ondes sismiques SH. Les résultats ont été exploités à partir du programme SHAKE, en utilisant l'accélérogramme du séisme de Lisbonne daté du 28/2/1969. Cet analyse permet de vérifier l'existence de grandes amplifications du sol, pour des basses fréquences, en tenant compte l'épaisseur alluvionnaire de chaque endroit.

1 INTRODUCTION

Portugal's capital, Lisbon, has suffered since the beginning of times the effects of several earthquakes, usually divided in two categories: interplate (Eurasian and African plates (Fig. 1)) and intraplate source event.

The strongest event which affected Lisbon's region belongs to the first group - the 1755 earthquake (estimated magnitude $M_L = 8.5$); while the 1909 Benavente earthquake ($M_L = 6.7$), is an intraplate event.

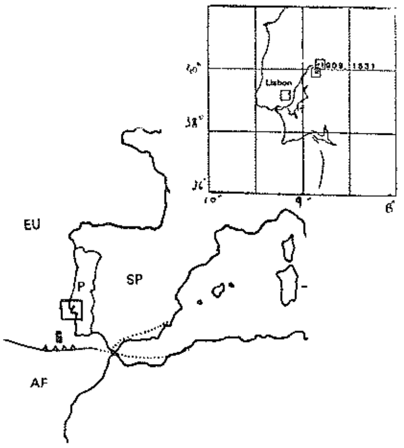

Fig. 1 - Portugal's tectonic emplacement.
Legend: EU - Eurasian plate; AF - African plate; G - Gorringe banc; P - Portugal; SP - Spain.

The 1755 earthquake caused the death of about 10% of Lisbon's population and destruction or damage in most buildings. However these damages weren't of the same dimension all over town - in the East zone the intensities were IX and X, while in the West the intensity was VIII (Pereira de Sousa, 1928). In the 1909 event, Benavente village (40 km NE of Lisbon) was almost destroyed and in Lisbon a different spatial damage distribution occurred: in the East zone - the most affected - the intensities were VI and VII, and in the West one the highest intensity was V (Zbyszewski, 1963).

These data lead us to conclude that it isn't the path or the source, the responsible for these differences, but the different geotechnical site properties. We're then dealing with the so-called Site Effects.

To validate theoretic models of some Lisbon's alluvial basins and of S. Jorge Castle hill produced with a seismic microzonation experiment realized in 1981, and to evaluate the site effects on those places a new field work was performed in October 1991 by the Geophysics Center of Lisbon's University in cooperation with the Laboratoire de Geophysique Interne et Tectonophysique of Grenoble, France. Fourteen portable seismic stations were used to record the seismic impact produced by three explosions made at the Tagus river (Fig. 2). For the results here after presented only those records from shot B were used.

2 SITE EFFECTS

The main site effects are the changes produced in the seismic signals spectrum, namely amplification and resonance in surface layers. Such effects can only be considered site effects if it happens always, whatever the seismic action may be, i.e. if for each site and for different earthquakes, the spectrum and the damage distribution change in the same way.

If the observed effect is common to several sites, it will be difficult to distinguish between source and site effects. The most favourable geologic structures for producing site effects are the alluvial basins and topographical accidents.

The main methodology used to study local effects is spectral analysis of displacements, velocity or acceleration records made at rock and alluvium sites (Fig. 3) during the same seismic action. Those made in outcropping rock site are considered representative of the motion in bedrock beneath alluvial station.

Building damages are mainly produced by horizontal motions - vertical motions amplitudes are 2/3 of horizontal ones, in average. Most methods used to study the effects of local site conditions are based in the assumption of main soil motion being caused by upward propagation of shear waves from underlying rock formations laid in planner, horizontal layers with infinite lateral extension. In the far-field case, source and path effects, specially the last one, are the most important; while in the near-field site effects cannot be neglected. With these assumptions we have in the first layers, a one-dimensional vertical propagation of shear waves due to bedrock vibration.

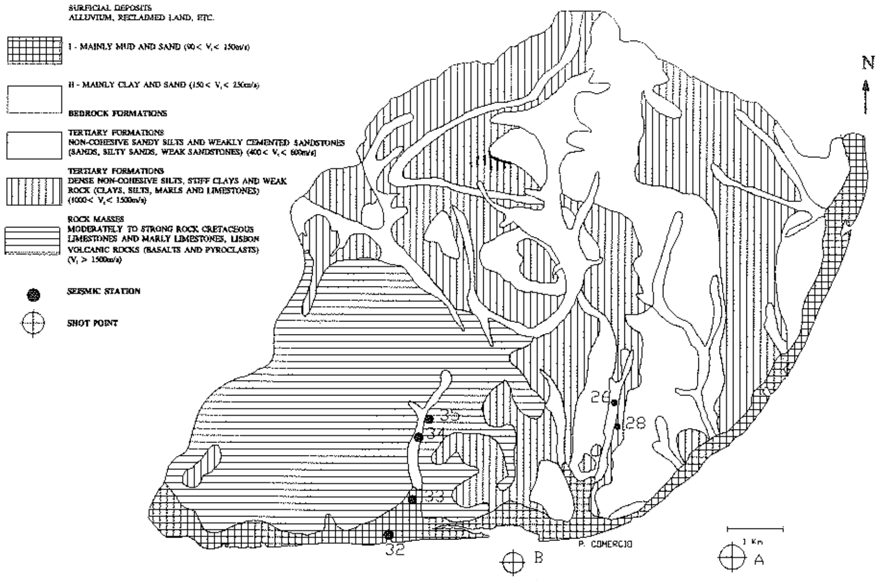

Fig. 2 Geotechnical map of Lisbon, with seismic stations location (adapted from Teves Costa and Mendes Victor, 1992)

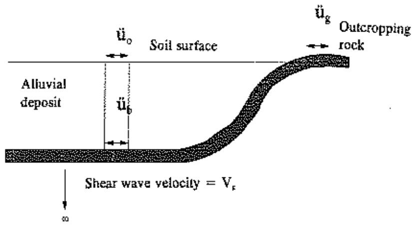

Fig. 3 - Soil and rock configuration.
Legend: $\ddot{u}_o$ - max. acel. in outcropping rock; $\ddot{u}_b$ - max. acel. in the same rock formation but under a soil column, and $\ddot{u}_g$ - max. acel. at surface (adapted from Lysmer et al., 1971).

Analytical methods used to predict the soil response are mainly based in the following points (Aki, 1988; Crespellani and Madiai, 1991; Schnabel et al., 1972):

1. Determination of the characteristics of the motion likely to develop in rock formation underlying the site, and selection of an accelerogram with these features, usually of strong motions.

2. Determination of soil deposit dynamic properties: average relationships for dynamic shear modulus (G) and damping ratios for soils (η), as functions of effective shear strain (γ).

3. Computation of soil deposit response to bedrock motions: a one-dimensional method can be used if the soil structure is essentially horizontal. This analysis is usually based on the solution to the wave equation, if the motion on rock underlying the soil column is known. However the main information available on rock motions comes from surface stations, so motions in the underlying rock will only be the same as in surface if we consider rock as a rigid layer.

Dynamic soil behaviour depends on the intensity of seismic action - since shear strains are a function of seismic action -, and it will be linear and elastic if the produced strains are less than 10^{-4}, which is the value associated with the propagation of seismic waves (Coelho, 1991; Seale and Archuleta, 1991).

If this value is overcomed, which happens easily with strong motions, it's necessary to account for the nonlinear characteristics of the soil. Their effects are usually felt in the reduction noted on the maximum amplification and its associated frequency - bigger intensity gives bigger reduction -, this is caused by strong damping produced by the soils histeretic behaviour, and in the attenuation increase with the deformation increase (Bard, 1983; Joyner and Chen, 1975).

3 ALCÂNTARA AND ALMIRANTE REIS AV. BASINS MODELLING

3.1 *Preliminary considerations*

Having in mind the ideas so far presented, geologic and geotechnical data were collected from different previous works (Mendes Victor, 1987; Teves Costa, 1989), and from the geological map of Lisbon county (Almeida, 1986) (Tables I and II).

Table I. Geotechnical features estimated for Lisbon's geologic formations (Coelho, 1985).

Type of formation	Formation	Mass density (g/cm^3)	Shear waves velocity (m/s)
Surficial deposits (Embankment, alluvium, etc.)	Mainly mud and sand	≈ 1.6	90-150
	Mainly clay and sand	≈ 1.8	150-250
Bedrock	Non-cohesive, sandy silts and weakly cemented sandstones (tertiary formations)	≈ 2.0	400-600
	Dense non-cohesive silts, stiff clays and weak rock (tertiary formations)	≈ 2.2	1000-1500
	Moderately to strong rock (Cretaceous limestones and Lisbon volcanic rock)	> 2.4	> 1500

Table II. Geographic parametres and geology in each station.

Station	Epicentral distance (km)	Altitude (m)	Geology
26	3.56	45.0	≈5 m al over M_{III}^2
28	3.16	35.0	M_{III}^2
32	2.15	3.0	≈33 m al over β
33	2.10	5.0	10-20 m al over C_c^3/β
34	2.78	12.5	10-15 m al over C_c^2
35	2.93	30.0	C_c^2

al - alluvium
M_{III}^2 - Entrecampos limestones
β - Lisbon's basaltic complex
C_c - Cenomanien carbonic complex

The strong motion accelerogram used for modelling was recorded in the North pile of Lisbon's Tagus river bridge, during the 1969/2/28 earthquake, with maximum acceleration 0.0261g (25.6 cm/s^2). Corresponding to the E-W component, it was digitized at the LNEC, and interpolated with equal intervals of time (0.02 sec) (Fig. 4).

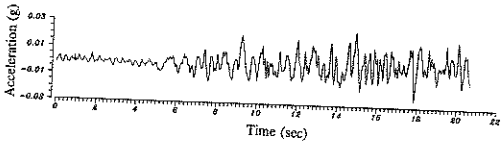

Fig. 4 - Accelerogram recorded in the North pile of Lisbon's Tagus river bridge, in 1969/2/28.

Alcântara basin has the highest alluvium thickness of Lisbon town - over 15 m -, while in Almirante Reis avenue basin thickness is hardly over 5 m. The surficial stratigraphy present in both basins is embankment and alluvium.

The geotechnical parameters that can be used to describe the soils nonlinear behaviour, namely damping and shear modulus, were estimated from standard relationships (Seed and Idriss, 1970 *in* Shannon and Wilson Inc., 1972) - those adopted for clay and sand are presented in Fig. 5-7.

For each basin the data processing started with the shot window identification in each station record, each with 10.24 sec long, where some noise was included, before and after the explosion. Than each station's spectrum was computed and, finally it was established the ratio between each alluvium station spectrum and that of the reference station in outcropping rock of the same bedrock formation beneath alluvium stations.

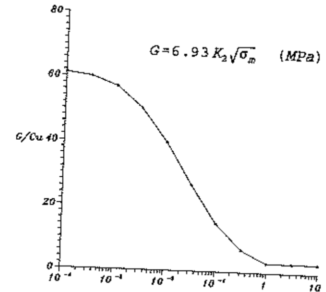

Fig. 5 - Shear modulus used for sand (D_r=75%).

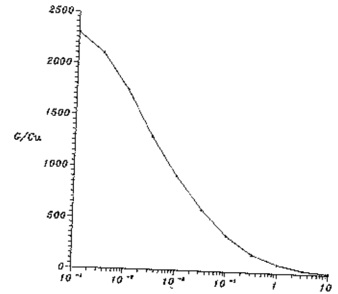

Fig. 6 - Shear modulus used for clay.

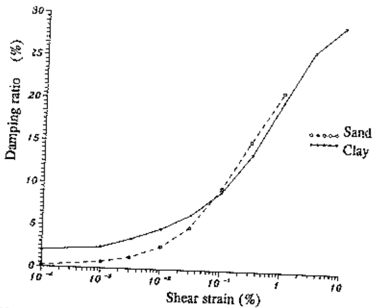

Fig. 7 - Damping ratio.

In alluvial deposits the lower frequencies are the most important ones. So, the aim was to reach a model that could adjust both in amplitude and in frequency the first maximum of amplitude the resulting ratio between the transverse components (TR) of Fourier spectrum, having always in mind each station's geology. The probable source of other maximums is bidimensional structures.

This analysis was always done until 8 Hz. Implicit hypothesis present in the method used by the SHAKE program of upward incidence of shear waves lead to only use of transverse components.

The results produced by the SHAKE program were smoothed with a polynomial function of 10 degrees.

3.2 *Alcântara basin*

In Fig. 8 we can see the velocity records made in Alcântara basin seismic stations - stations 32 (Santo Amaro dock embankment), 33 (Alcântara square), 34 (Ceuta av.) and 35 (Arco do Carvalhão street). A Butterworth filter band-pass (0.2-15 Hz) with 8 poles was applied to these records.

The produced displacements were less or equal to 10^{-4}, so a linear soil behaviour can be considered.

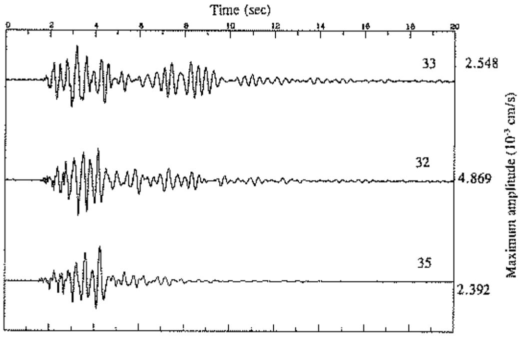

Fig. 8 - Display of velocity records made in stations 32, 33 and 35 - transverse components.

Analysing the velocity records we can see that in soil stations amplitudes are bigger and longer in time than in outcropping rock formation (station 35). In station 33 the signal length of time is approximately 8 sec, while in station 35 it is a little over 4 sec.

Signal length of time is longer in station 33 than in station 32. We would expect the opposite because this station has a bigger alluvium and embankment thickness than that one. A possible explanation to this is the compaction level present at both places. It is possible that the compaction degree produced by the construction of Santo Amaro dock embankment is greater than that one produced with filling of Alcântara streamlet.

In the low frequencies of spectral ratio between transverse components of stations 32 and 33 it can be seen two leading maximums, with amplitudes 6 and 8 at 2.4 and 5.2 Hz, respectively (Fig. 9). In the theoretic results (Fig. 10), we have a first maximum at 2.4 Hz, with amplitude 4 and a second one at 6 Hz, but with smaller amplitude; the third one is over 8 Hz (9.2 Hz), but we can consider that it matches the maximum at 8.8 Hz in the experimental data.

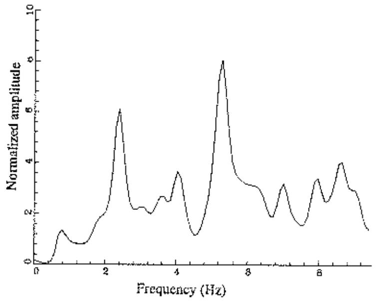

Fig. 9 - Spectral ratio between stations 32 and 35 for transverse components.

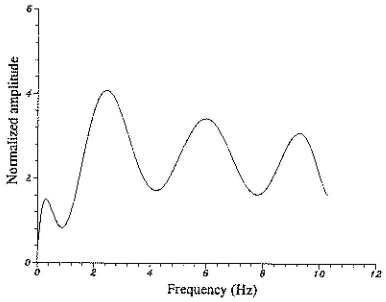

Fig. 10 - Theoretic spectral ratio

In Table III we have the theoretic model that produced these results, where η stands for the critical damping ratio and *Factor* is a multiplier applied to the shear modulus relationships (Fig. 5 and 6). The result for the total thickness of soil deposit is only 10% higher than that estimated from Lisbon's geological map (Table II).

Table III. Station 33, theoretic model parameters.

Soil type	Thikness (m)	η	Mass density (g/cm^3)	V_s (m/s)	Factor
Clay	9.1	.05	1.76	230	0.9
Sand	9.1	.10	1.84	116	1.1
Sand	15.2	.10	1.92	137	1.9
Bedrock			2.72	2000	
Total	33.4				

Spectral ratio between stations 33 and 35 (components TR) shows three main maximums with amplitudes 3.0, 2.6 and 2.7, at 2.4, 4.0 and 5.6 Hz, respectively (Fig. 11). Theoretic spectral ratio (Fig.12) has a first maximum with amplitude 2.9 at 2.9 Hz, which matches both in amplitude and in frequency with the first field maximum. With the second one this doesn't happen because thickness of alluvial soil in station 33 is very small, which doesn't allows the use of more layers in the theoretic model, presented in Table IV.

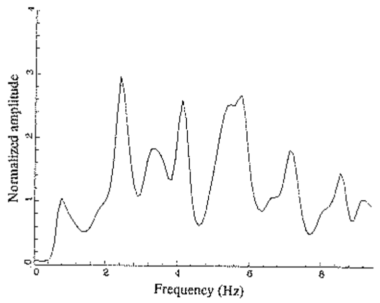

Fig. 11 - Spectral ratio between stations 33 and 35 for transverse components.

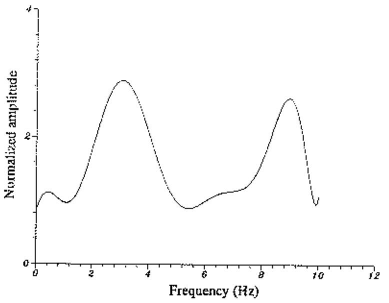

Fig. 12 - Theoretic spectral ratio

Table IV. Station 33, theoretic model parameters.

Soil type	Thikness (m)	η	Mass density (g/cm³)	V_s (m/s)	Factor
Clay	12.2	.05	1.76	213	0.9
Sand	1.5	.10	1.92	107	1.2
Bedrock			2.72	2000	
Total	13.7				

Since station 34 only had vertical component (VR), it was decide to estimate the probable model from those of stations 32 and 33, since all three stations have almost the same epicentral distance, the geology beneath them is the same and they aren't very far apart (Table II).

Analysing the vertical component of the three stations (Fig. 13) we can see that they have almost the same shape. However, spectral amplitude in station 34 is higher than in station 33. In figure 14 we have both stations 32 and 33 spectral ratios where it can be seen that station 32 has a higher amplitude ratio. So the alluvial soil thickness beneath station 34 might be higher, and the amplitude ratio in station 34 will not differ very much from that one in station 33.

In figure 15 we have the theoretic spectral ratio for station 34 and its model in Table V. The first maximum (3.2) is at 2.4 Hz, such as in station 33 but 10% higher, which validates the considered hypothesis. In this station we also have a good agreement between estimated values (Table II) and those from modelling.

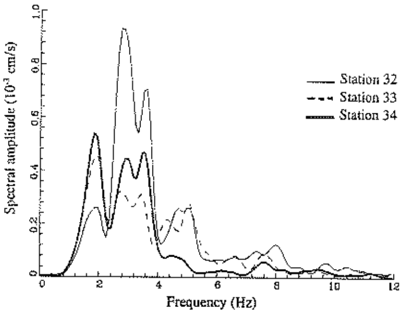

Fig. 13 - Velocity spectrums - Comp. VR

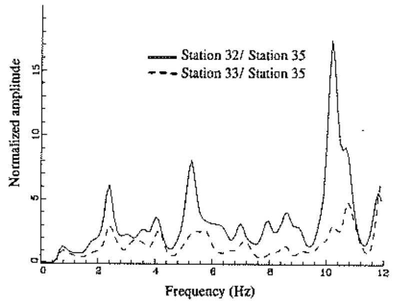

Fig. 14 - Spectral ratios for transverse components.

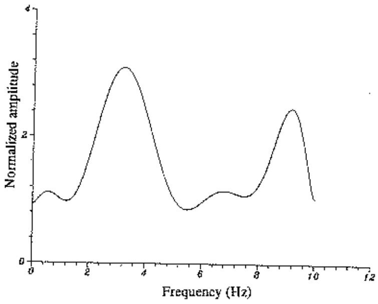

Fig. 15 - Theoretic spectral ratio

Table V. Station 34, theoretic model parameters.

Soil type	Thikness (m)	η	Mass density (g/cm^3)	V_s (m/s)	Factor
Clay	12.5	.05	1.68	213	0.9
Sand	0.6	.10	1.84	122	1.2
Bedrock			2.72	2000	
Total	13.1				

3.3 *Almirante Reis avenue basin*

For modelling this basin we only had two stations: 26 (António Pedro street) and 28 (Anjos Churc), whose records are plotted in Fig. 16, after being filtered like in Alcântara basin.

The alluvial soil thickness in station 28 is very low (Table II), wich once again doesn't allows the use of more layers in the theoric model.

Spectral ratio between stations 26 and 28 has two main maximums, with amplitudes 3.4 and 3.2, respectively at 3.8 and 6.8 Hz (Fig. 17).

Comparing the theoretic results (Fig. 18) and the field ones we can see that they only adjust in frequency - the maximum for the theoretic spectral ratio appears at 4.2 Hz.

For a better adjust two other velocities were considered for the bedrock formation. The lower values - 1200 and 1500 - have already been used in 1D linear analysis, for the same basin (Teves Costa, 1989) and the higher value was considered from the results obtained with the last field work (MendesVictor, 1987).

The difference between the maximum in the highest velocity spectral ratio (4.9) and the lowest (4.5) is only 0.4 ($\approx 10\%$), which isn't very significant.

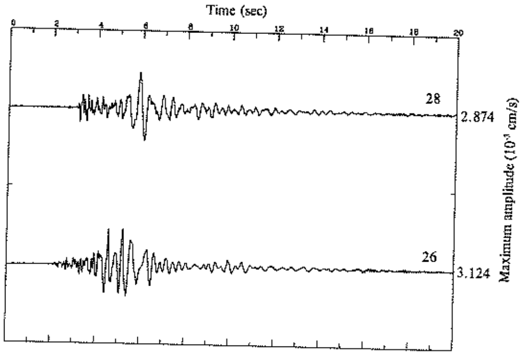

Fig. 16 - Display of velocity records made in stations 26 and 28 - transverse components.

The theoretic model considered for this basin is presented in Table VI (the three models used in this basin were only different in the shear velocity for the bedrock formation).

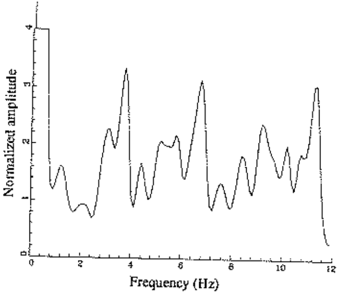

Fig. 17 - Spectral ratio between stations 26 and 28 for transverse components.

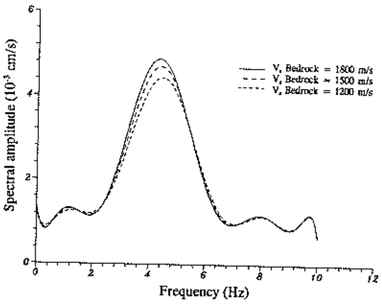

Fig. 18 - Theoretic spectral ratio

Table VI - Station 26, theoretic model parameters.

Soil type	Thikness (m)	η	Mass density (g/cm^3)	V_s (m/s)	Factor
Clay	10.0	.05	1.76	250	0.9
Bedrock			2.72	1500	
Total	10.0				

4 DISCUSSION

The estimation of some essential parameters such as shear velocity and mass density bring on some difficulties for modelling, however the achieved models are representative of the reality.

In shallow sites the results weren't very good because it was very difficult to have more layers with such low values for thickness.

The theoretic models produced allowed to verify the great importance of surficial layer, mainly clay.

Considering the existence of several stations in alluvial soil, in Alcântara basin, it was possible to note a certain amplitude function of the alluvium thickness, since the epicentric distance of these basin stations didn't differ very much, specially between stations 32 and 33 (Table II).

5 CONCLUSIONS

Theoretic values of thickness and mass density obtained for these basins have a good match with estimated ranges (Table I).

In Alcântara basin we have an alluvial deposit with thickness between 13m at the begining and 33m near Tagus river, over Lisbon's volcanic rocks (V_s=2000 m/s). Almirante Reis basin has a thinner alluvial deposit over less cohesive rock - Miocenic limestones (V_s=1200 m/s).

With this one-dimensional linear equivalent method it was possible to produce good results on the deeper sites of Alcântara alluvial basin with good fitness between theoretical and field results.

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