4th International Conference on
Earthquake Geotechnical Engineering
June 25-28, 2007
Paper No. 1446

ESTIMATION OF SITE EFFECTS MODELLING PARAMETERS USING A GEOTECHNICAL DATABASE

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ABSTRACT

In spite of the growing use of cost-effective geophysical techniques to characterize the near-surface structure (surface wave methods and noise array measurements) geological and geotechnical information is still important not only as primary source but also for calibration support.
More than one hundred years of geological and geotechnical investigation in Lisbon produced a large amount of information that has been processed with special focus on the elaboration of geological mapping and geotechnical characterization.
The great advance in computational tools allowed setting up a geotechnical database, which integrates different kinds of information included in geotechnical reports. The evolution of in site investigation techniques as well as different practices adopted by different companies, leads to non-uniform data. These problems were taken into account in the construction of a friendly GIS geotechnical database with engineering geological mapping purposes.
The geotechnical database can be used to estimate the relevant parameters for site effects modelling. With this purpose it is necessary to select the adequate data fields needed to calculate site effects parameters, such as lithology, thickness, N(60), seismic wave velocities, density and PI.
In this paper, the application of this procedure to a selected zone in Lisbon is presented. This zone was recently rehabilitated to hold the 1998 international exhibition. Located near the Tagus River it includes different geological materials, with Miocene bedrock, very soft alluvial deposits and a shallow coverage of surficial fills. The huge urban development of the area produced a large amount of geotechnical data.

Keywords: Lisbon, geotechnical database, geotechnical characterization, site effects.

INTRODUCTION

Ground motion amplifications over sedimentary sites during strong earthquakes often cause severe damage. This effect, known as “site effect”, is due to the geotechnical and physical properties of the near-surface layers. Many examples exist which demonstrate the importance of the near-surface geology on the transmission of the seismic energy and on the modification of the seismic signal (Bucharest, 1977; Mexico City, 1985; Kobe, 1995; etc.). So, it is very important to identify and estimate potential site effects in a region with moderate or high seismic hazard.

As it is well known, Lisbon has been struck by a strong earthquake in 1755 (with an estimated magnitude close to 8.5). During the 20th century the town was affected by only one strong earthquake, on February 28th, 1969, with magnitude 7.9. In spite of this apparently “low” seismicity, the seismic

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risk in Lisbon is moderate, due to the economic and social importance of the town and taking into account the historical seismicity. However, due to this low seismicity, there are only a few strong motion stations in Lisbon and a very few seismic records of small earthquakes (less than magnitude 4).

The estimation of site effects is usually done by SSR, which is the spectral ratio between the seismic signal recorded in a rock site (reference station) and the signal recorded in a sedimentary site (or the studied site). However, in regions with low seismicity, due to the lack of seismic records, methods based on noise measurements (H/V analysis and array technique), recently developed, are widely used. In spite of the low cost of these methods, they include field experiments and they are very sensitive to the field conditions. Theoretical simulation, 1D and 2D, are still used and necessary to understand and validate the results of the noise analysis. To do it, knowledge of near-surface geology, physical parameters (such as shear wave velocity, thickness, density) and interface geometry (2D), is needed.

The knowledge of the geological setting was used to carry out a first 1D theoretical approach (Teves-Costa et al., 2001). Taking advantage of the large amount of geotechnical data obtained in the rehabilitation and urbanization of a small area in the eastern part of Lisbon (Figures 1 and 2), it is possible to estimate the necessary relevant physical parameters of the shallow layers. The collected geotechnical data are incorporated in the Lisbon Geotechnical Database which is associated to a Geographic Information System (Almeida et al., 2003). The methodology used to estimate these parameters is presented in this paper.

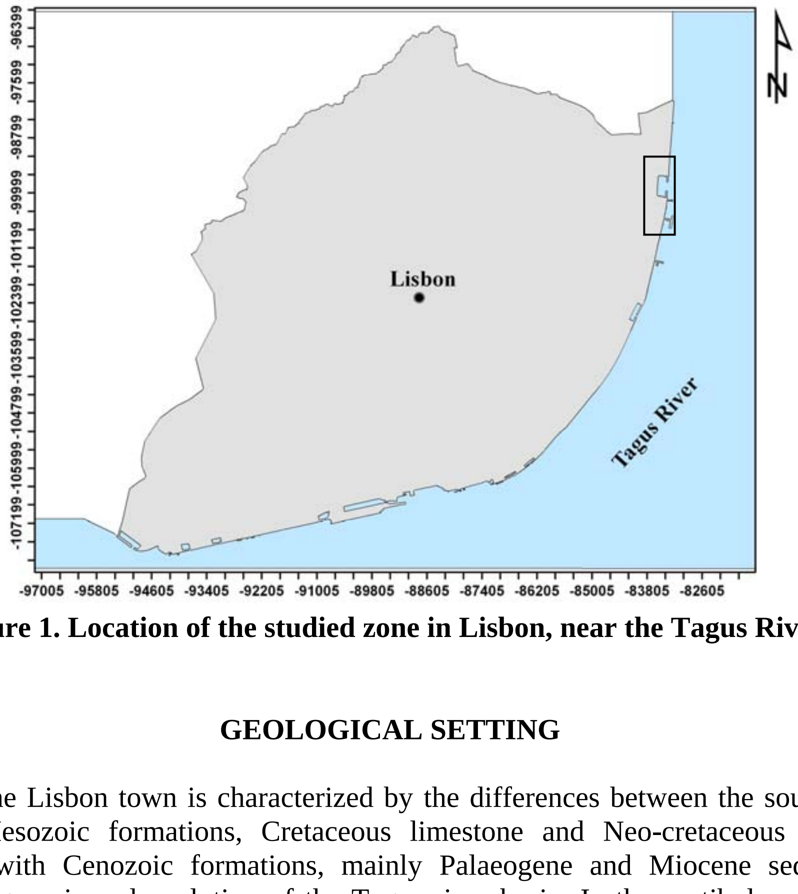

Figure 1. Location of the studied zone in Lisbon, near the Tagus River.

GEOLOGICAL SETTING

The geology of the Lisbon town is characterized by the differences between the south-western area, landscaped in Mesozoic formations, Cretaceous limestone and Neo-cretaceous basalt, and the remaining area, with Cenozoic formations, mainly Palaeogene and Miocene sedimentary series associated to the genesis and evolution of the Tagus river basin. In the vestibular area of the River Tagus, the Cenozoic deposits start with a reddish conglomeratic continental series (Oligocene). During the Miocene, an open connection with the sea allowed the deposition of a quite complete estuarine sequence, with alternate marine and continental facies. The thickness of the complete sequence can attain approximately 300 meters (Cotter, 1956). As the Miocene forms a monocline dipping eastwards, the sequence is thinner in the West, and becomes thicker eastwards. The Pliocene and the Pleistocene sedimentation represent a new organization in the basin with a predominantly sandy sequence. The actual Tagus configuration was formed about 18 000 years ago, with the sea-level 120 m below the actual position. The evolution of the basin was dominated by variations in the sea-level, generating several terrace levels. The Holocene fluvial infill is characterized by a sequence of sandy and clayey lenticular beds with lateral and vertical facies variation.

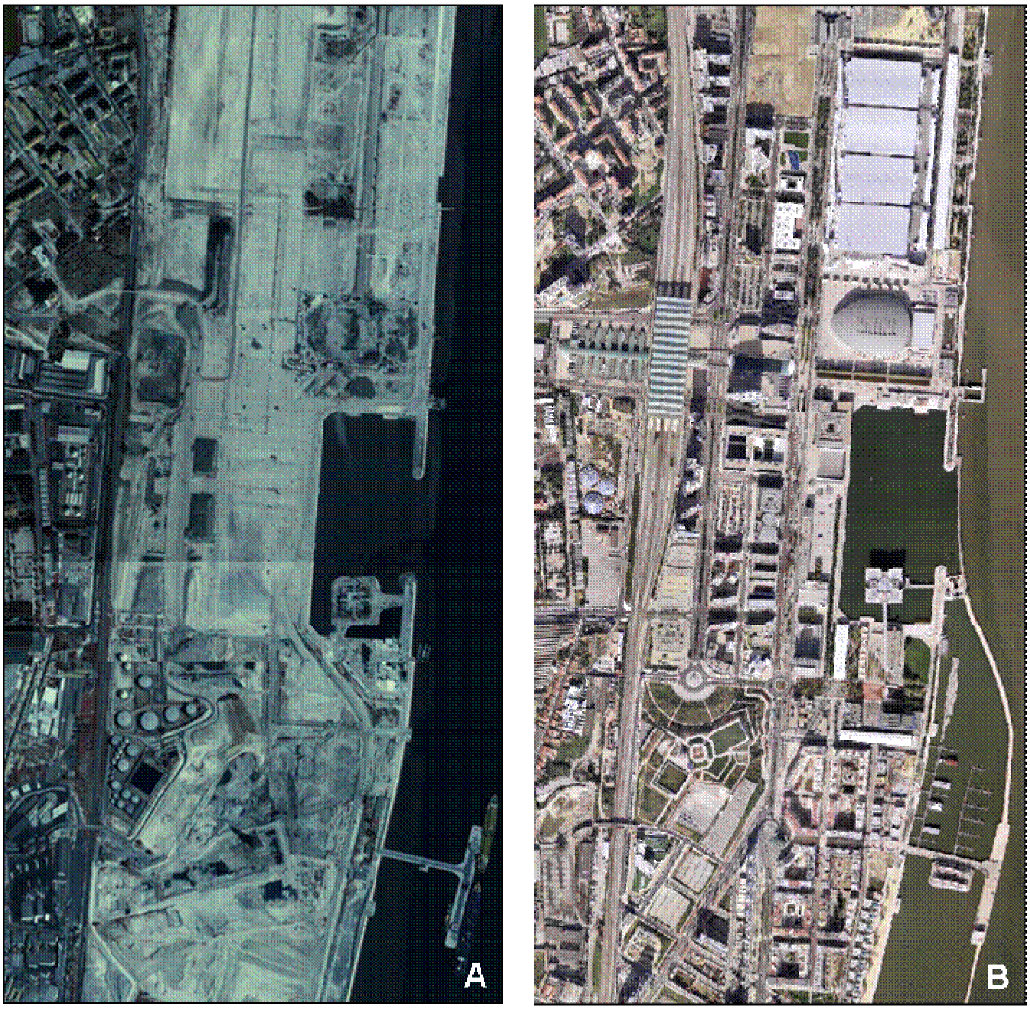

Figure 2. Aerial photograph of the studied zone: A – during the rehabilitation process (1996); B – after the urbanization (2006).

In the study area the geological setting is characterized by Miocene bedrock covered by alluvium (from the Tagus River and from tributary small streams) and artificial earth fills associated to the coastal reclaimed area (Figures 3 and 4). The local Miocene formations represent the top of the Lisbon region sequence (Cotter, 1956), described in the end of 19th century when many of these formations could be observed in the new outcrops of the railway trenches and stone quarries excavated for the construction of the reclaimed area, namely: M_{VIIb} – "Areolas de Cabo Ruivo"; M_{VIIa} – "Areolas de Braço de Prata"; M_{VIc} – "Calcários de Marvila" and M_{VIb} – "Arenitos de Grilos".

The earth fill unit is very heterogeneous, predominantly clayey, sandy or clayey sands, sometimes with very coarse block and showing anthropic activity (Almeida, 1991). Part of the studied zone corresponds to a reclaimed area, mainly constructed in the end of the 19th century and completed during the recent rehabilitation works. The old embankment is frequently buried in the soft alluvial deposits. The past industrial activities in the area caused an extensive soil contamination. During the rehabilitation process of the area part of these soils were removed.

The Tagus alluvial deposits are mainly muddy, rich in organic matter, intercalating with clean sands. The lenticular lateral variations are common, varying in composition, consistency and density, and often presenting shells or its fragments (Almeida, 1991). The secondary streams alluvial deposits are very dependant on their sedimentary source but are sandier than the deposits of the Tagus River.

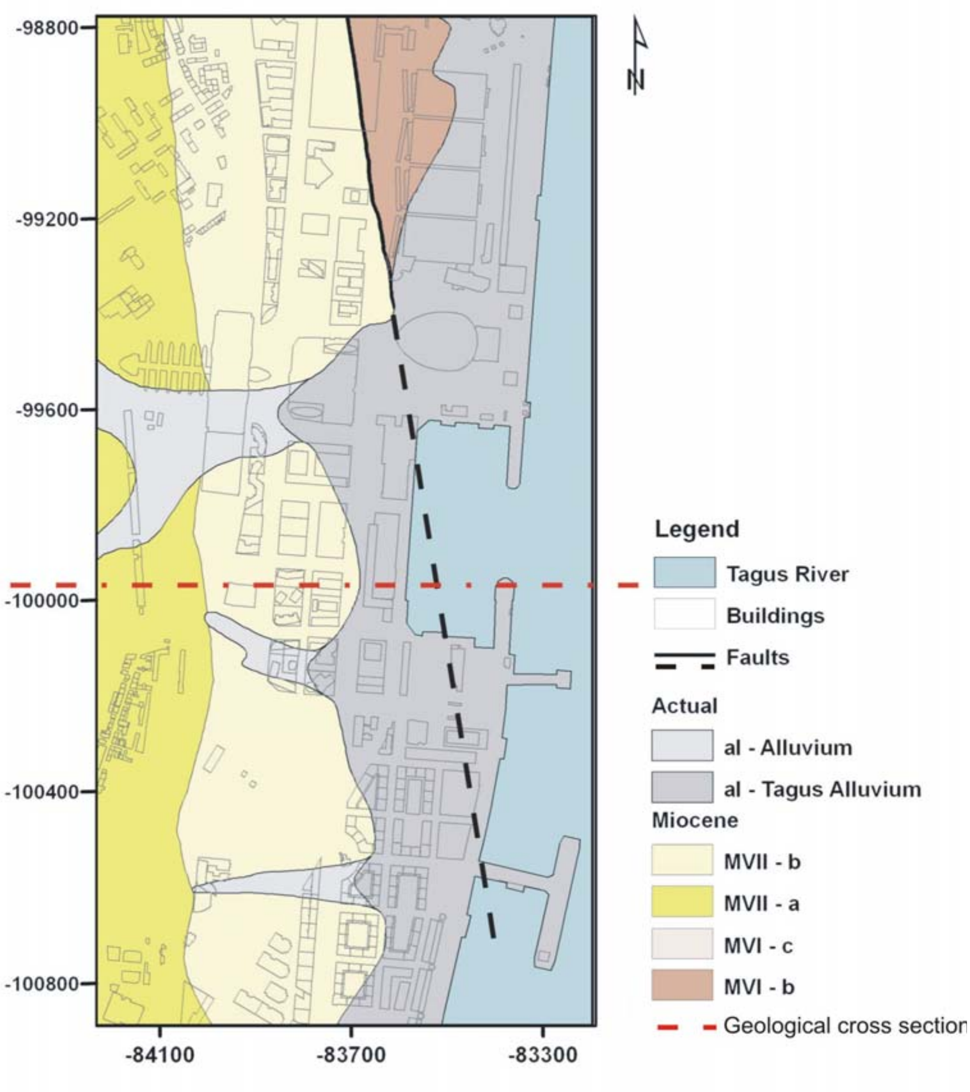

Figure 3. Geological map of the studied area and geological cross section (Figure 4) location.

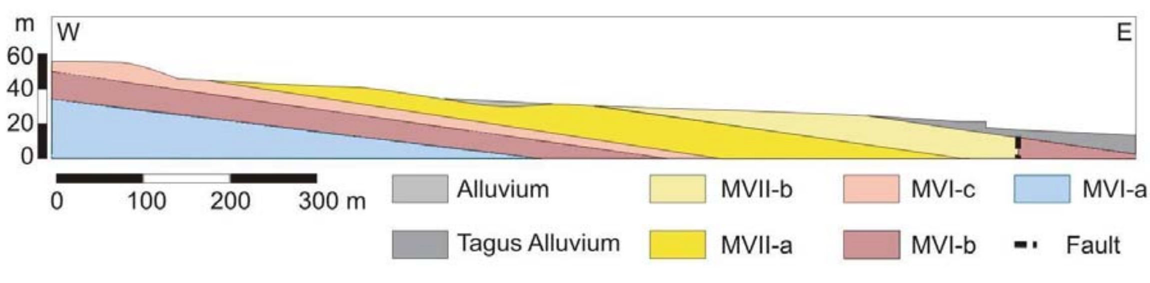

Figure 4. Geological cross section.

The two upper Miocene formations “Areolas de Cabo Ruivo” (M_{VIIb}) and “Areolas de Braço de Prata” (M_{VIIa}) are characterized by the presence of thick layers of fine micaceous sand (“*areolas*”), intercalating with thin marly limestones (M_{VIIb}) and with clayey layers, sandstones with coarse sediments and fossil-rich layers (M_{VIIa}). The predominance of clayey intercalations as well as the intensity of coloration due to the presence of iron oxides was used to distinguish between the two formations. This separation which was probably evident in the reference outcrops is very difficult to establish in the borehole interpretation. The total thickness of these two formations can reach up to 40 meters.

The "Calcários de Marvila" (M_{VIc}) and the "Arenitos de Grilos" (M_{VIb}) formations are composed mainly by limestones (*"calcários"*) and sandstones (*"arenitos"*) with many fossils; the sandstones are very compact and composed by fine micaceous to coarse sands with calcareous to ferruginous or siliceous cement; the limestones are marly and very stiff. The total thickness of these two formations can reach up to 25 meters. As well as for the previous formations the separation described in the literature in terms of predominant lithology and intensity of coloration is very difficult to establish in the borehole interpretation.

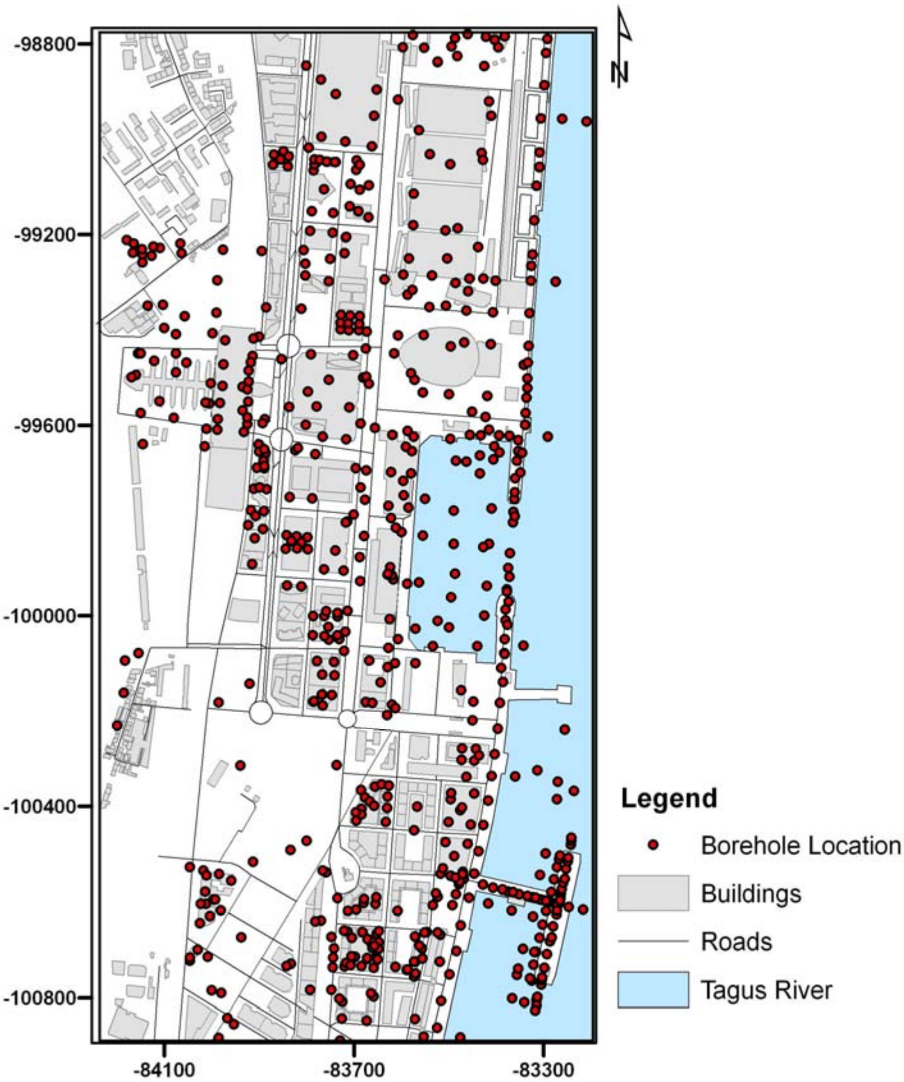

Figure 5. Geotechnical boreholes location.

GEOTECHNICAL CHARACTERIZATION

Before the rehabilitation of the area to hold the EXPO 98 some boreholes were available, concentrated in the limit of the old quay. In the last decades the zone was occupied by industrial activities, mainly oil refineries partially neutralised with its consequent degradation. In the rehabilitation project it was intended to construct not only some temporary buildings for the exhibition but also some permanent constructions and, in particular, to improve the structure of the global network to allow the management of a future residential area with high quality. In order to attain these short and long term objectives a large number of geotechnical studies were developed and are still being done.

In the selected area of about 2 km^2 it was possible to pick from the Lisbon Geotechnical Database 622 boreholes, crossing 8356 meters of different stratum (Figure 5). The depth of the boreholes range from 1.9 m to 58.9 m but 85% has less than 20m and the value of the mode and median is 12 m. Standard penetration tests (SPT) were performed in 577 boreholes; a total of 3677 tests were collected and the corresponding lithology and stratigraphy were identified.

The database is prepared to input raw data, with a minimum of interpretation necessary to balance the subjectivity and omissions that characterize this kind of data. Each borehole is associated with a geotechnical report and includes the geographic location (x,y) and elevation head, the lithological description (main lithology and colour and corresponding thickness) and stratigraphic description (formation identification and corresponding thickness). Each SPT test is associated to the respective borehole, including the geographic location (x,y) and borehole elevation head, depth of the beginning and end of the test, blow count (N), main lithology and stratigraphic formation. Some of the geotechnical reports include also laboratory data not yet integrated in the database.

The boreholes cross different stratigraphic formations, including the surficial deposits (surficial fill and alluvium) and the Miocene bedrock (M_{VIIb}, M_{VIIa}, M_{VIc} and M_{VIb}) with different percentages, which can be calculated considering the stratigraphic interpretation in each borehole, the thickness sum and SPT data (Table 1).

Table 1. Distribution of SPT tests and geological units thickness crossed in the boreholes.

	SPT	Thickness
Surficial fill	12%	16%
Alluvium	20%	20%
M_{VIIa}	59%	55%
M_{VIIb}	5%	5%
M_{VI}	5%	4%

Lithological composition

The different complexes present the same lithological types with different proportions and degree of consolidation. The analysis of the lithological distribution can be performed considering the measured sum of the layers thickness for each type (Figure 6).

Considering that in the studied area the stratigraphic identification of the bedrock formations is not easy to perform due to the lateral and vertical variation of facies, it becomes necessary to simplify, considering the different formations in a single complex, designated as Miocene.

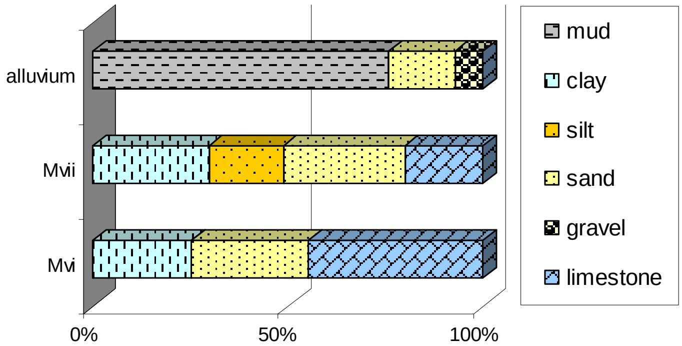

Figure 6. Lithological composition.

Surficial deposits

In the majority of the situations (98%) the Miocene bedrock is covered by alluvium and/or surficial fill (Figure 7 and Table 2). The spatial distribution of these two types of materials depends on the borehole location. The surficial fills are present in 74% of the boreholes while the alluvial deposits were intercepted in 55% of the boreholes. The deepest surficial fills, mainly associated with the reclaimed areas, have a more uniform distribution than the alluvial deposits. The eastern part, adjacent to the river, presents the deepest alluvial deposits, increasing to east.

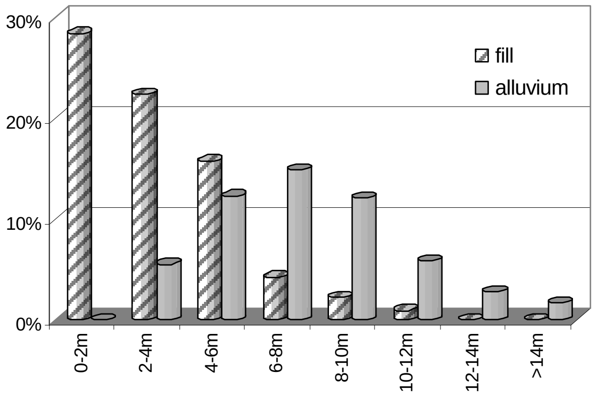

Figure 7. Thickness distribution of the surficial deposits in the boreholes.

Table 2. Statistics for the thickness of surficial deposits in 546 boreholes.

	fill	alluvium	Fill + alluvium
Mean	2.3	4.3	5.3
Median	1.6	4	4.6
Mode	0	0	6
Standard deviation	2.39	4.47	3.78
Minimum	0	0	0
Maximum	12	26	26

Standard Penetration Test

As for each test the value of N(60) can be computed for a penetration of 30cm and corrected to the length of the rods (Fernandes, 1995). The results were analyzed for each complex considering the lithological composition and the depth. The lithological composition has a relevant impact in the test but, due to lateral and vertical variation of facies it is quite impossible to analyze the spatial lithological distribution. In consequence the more efficient approach is to consider different depths.

The statistical distribution of these tests is covered up by the overemphasizing of very high values. In consequence, the traditional statistical parameters (mean and standard deviation) present exaggerated values, biasing the analysis. The values of the 1st, 2nd and 3rd quartiles (Q1, Q2 and Q3) allow a better statistical approach.

Surficial fill

With a total of 429 tests the surficial fill is characterized by the heterogeneity and the shallow depth (Table 3 and Figure 8).

Table 3. Statistics for N(60) in surficial fill.

	total	<5m	>5m
Mean	62	18	446
Mode	3	3	8
Standard Deviation	826	37	2572
Count	429	385	44
Q1	4	4	6
Q2	9	9	11
Q3	17	17	31

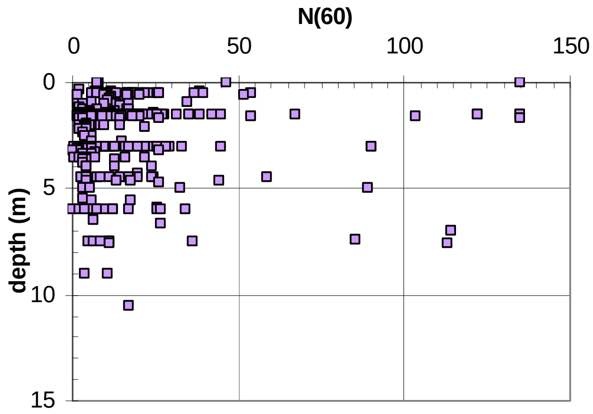

Figure 8. Distribution of N(60) SPT tests (n = 429) with depth in the surficial fill: 94% of values are less than 60 and 3% greater than 150.

Alluvium

With a total of 724 tests the alluvium is characterized by normally consolidated soils showing different behaviour depending on lithology and depth (Tables 4 and 5 and Figure 9).

Table 4. Statistics for N(60) in different alluvial lithological types.

	total	sand	gravel	mud
Mean	231	28	1035	11
Mode	0	21	122	0
Standard Deviation	1749	16	3705	14
Count	724	170	153	401
Q1	4	15	122	2
Q2	16	24	180	4
Q3	47	37	257	14

Table 5. Statistics for N(60) in alluvial deposits at different depth.

	<5m	5-10m	10-15m	>15m
Mean	9	106	590	551
Mode	0	0	180	26
Standard Deviation	42	923	2939	2870
Count	169	348	182	39
Q1	2	4	18	28
Q2	3	18	34	40
Q3	5	54	128	114

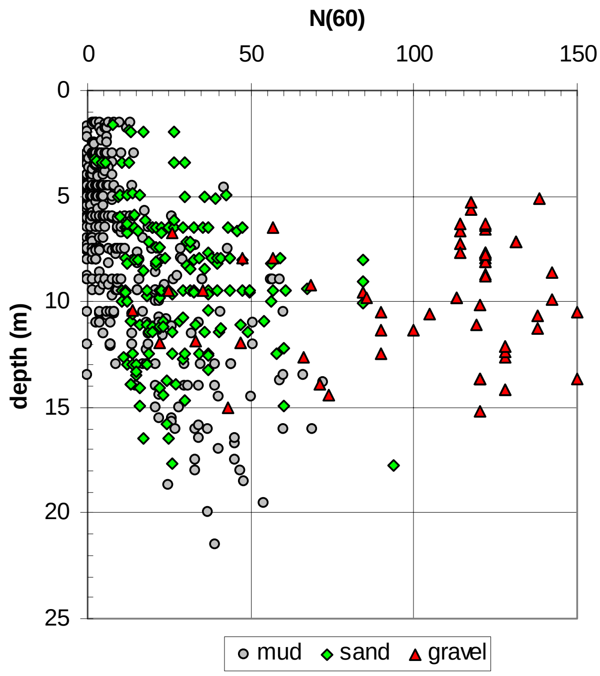

Figure 9. Distribution of N(60) SPT tests (n = 724) with depth in the alluvial deposits: 79% of values are less than 60 and 12% greater than 150.

Miocene

With a total of 724 tests the Miocene bedrock is characterized by the presence of overconsolidated soils with different behaviour between lithologies and variation in depth (Tables 6 and 7 and Figure 10).

Table 6. Statistics for N(60) in different Miocene lithological types.

	total	clay	silte	sand	limestone
Mean	200	70	55	71	972
Mode	60	60	19	60	180
Standard Deviation	1373	82	73	112	3475
Count	2524	699	568	885	372
Q1	28	30	23	24	114
Q2	49	45	34	48	180
Q3	94	72	57	72	341

Table 7. Statistics for N(60) in Miocene at different depth.

	<5m	5-10m	10-15m	15-20m	>20m
Mean	103	86	178	525	121
Mode	19	30	60	60	72
Standard Deviation	723	173	1208	2691	141
Count	469	677	665	478	235
Q1	15	24	35	45	60
Q2	22	33	54	62	74
Q3	51	61	119	120	144

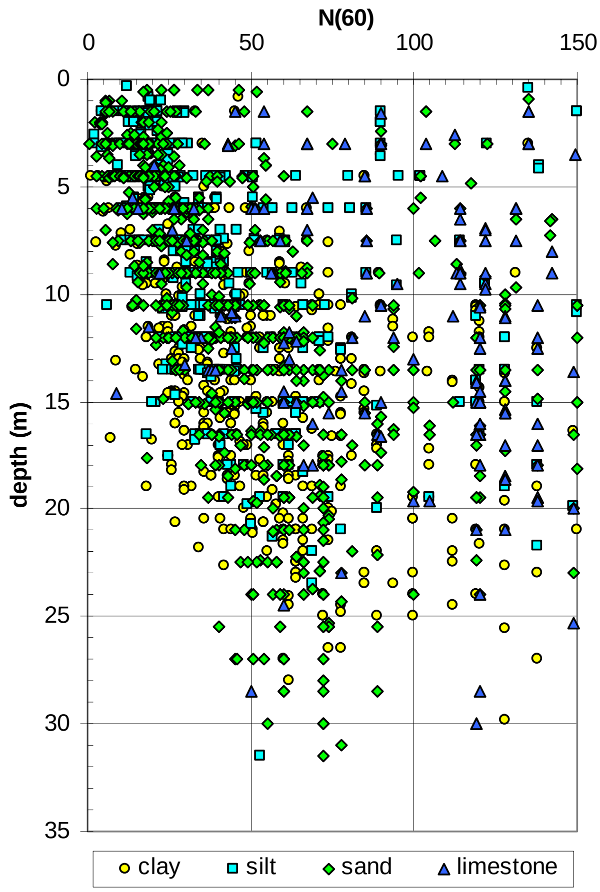

Figure 10. Distribution of N(60) SPT tests (n = 2524) with depth in the Miocene deposits: 61% of values are less than 60 and 15% greater than 150.

DISCUSSION

The amount of data collected, although not enough to determine all the relevant parameters for site effect modelling allows a good estimation of the physical properties of the shallow formations, the identification and location of potential site effects conditions and the more important gaps and errors in the datasets.

A borehole database, in conjunction with a DTM and geological maps, is essential to enable 3-D relationships of the geology, to be visualised and better understood. The amount of information to be introduced in the borehole database depends on the project objectives, the complexity of the geology and the available resources. The geotechnical database was constructed with the purpose of keep the data as raw as possible. The data processing enables the identification of different kind of errors in the location, in the depths, in the lithological and stratigraphical interpretation of log description and in situ test results. These errors can be due to different causes like wrong data introduction, bad interpretation or poor data quality, sometimes with more than one cause making difficult to identify the source of error.

In spite of these constrains the data can be used to produce a geological 3-D model that being a complex task need successive iterations. The data interpretation and integration allows the update of the surficial geology. The surficial geologic map presented in Figure 3 is an improvement (Almeida et al., 1997) of the previous published map (Almeida, 1986), showing a fault identified by borehole cross-section interpretation. One of the advantages of digital mapping is the fact that it can be easily and regularly updated (Culshaw et al, 2002).

The interpolation of the borehole data can also be used to produce the thickness contours of the alluvial deposits, which is an essential task in the geologic model (Figure 11). Besides the foreseeable model this map can be used to exemplify how wrong data can be check: close to the green arrow it is possible to observe a point with very thick alluvial deposits out of the probable limit; this can be due to wrong borehole location or wrong stratigraphic interpretation.

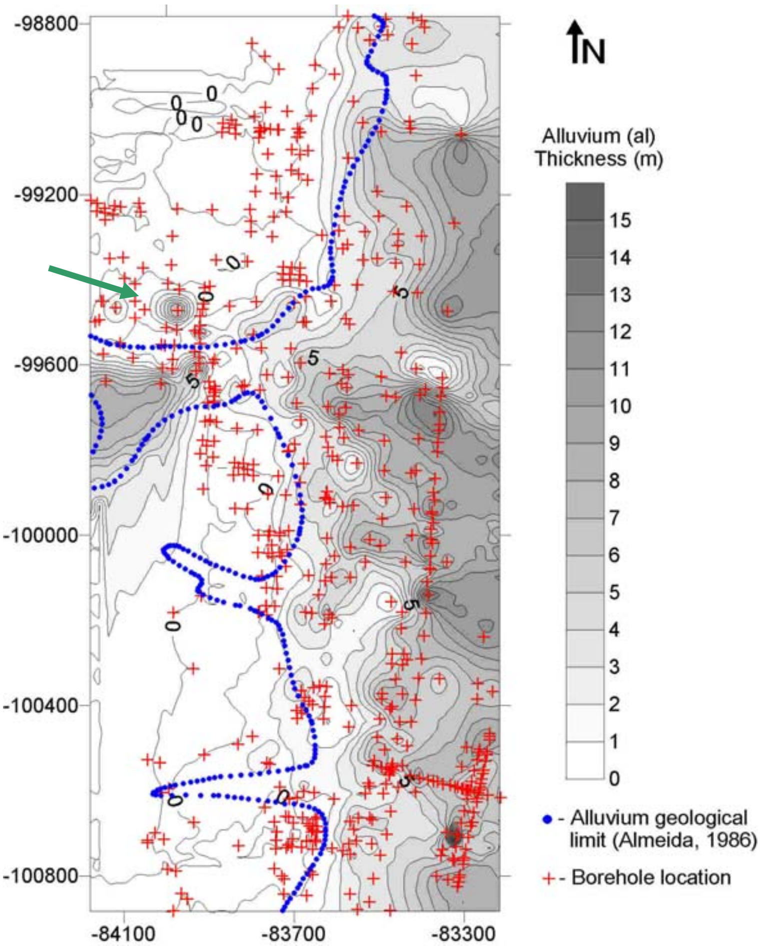

Figure 11. Isothickness contours of the alluvial deposits obtained from borehole data.

This approach is useful to improve the database quality through iterative checking of errors and corrections implementation.

The presence of high water levels, due to the vicinity of the river, represents one of the relevant geological conditions in the area. However in the majority of the boreholes the ground water elevation is not measured and piezometers are not installed. This is an important parameter especially because the surficial deposits (artificial fills and alluvium) contain lenticular layers of saturated loose fine sands, representing a potential liquefaction risk.

FINAL CONSIDERATIONS

The analysis of the geological and geotechnical investigation information, produced and processed with special focus on the elaboration of geological mapping and geotechnical characterization, can be used to estimate the relevant parameters for site effects modelling. With this purpose it is necessary to select the adequate data to calculate site effects parameters, such as water level, lithology, thickness, N-SPT, seismic wave velocities, density, medium grain size, fine content, moisture, and PI. The used borehole database, although insufficient to calculate all those parameters, allows a good estimation of the main properties and, due to the enormous amount of data, the spatial variability and the perception of the main gaps and errors in the information.

Although shear wave velocity could be obtained directly from field investigations or laboratory testing, the economical restraint represent an important limitation. When the direct measurement of shear wave velocity for soil layers is not available, the existing or developed correlations between N values of SPT and the shear wave velocity could be used. Many empirical relations were proposed since the 60’s by different authors, for different types of soils. Jafari et al. (2002) present an extensive bibliographic compilation.

The construction of important engineering projects like the EXPO and the nearby Vasco da Gama Bridge represents a relevant source of data, as they include not only the regular tests but also more unusual tests. The amount of data is very extensive and described in several reports, many of them difficult to access, but representing an important source of information to be inserted in the geotechnical database. Oliveira et al. (1997) and Vieira et al. (1995) present an overview of the principal characteristics of the main geotechnical complexes. The availability of in situ, cross-hole measurements of shear-wave velocities allowed the comparison with our results (Table 8).

Table 8. Cross-hole measurements of shear-wave velocities in the EXPO and Vasco da Gama Bridge projects (Oliveira et a., 1997 and Vieira et al, 1995).

	Surficial fill	Alluvium		Miocene
		Muddy	Sandy	
EXPO	185 - 222	69 - 146	155 - 277	433 - 972
Vasco da Gama Bridge	---	51 - 246	111 - 309	460 - 882

This approach intend to be the start of a larger project, integrating the implementation of new data with laboratory tests and in situ geotechnical and geophysical tests, allowing to identify the local ground conditions according to the types defined in Eurocode 8 and to perform a large scale site effect modelling and seismic zonation. The use of geotechnical databases in a GIS environment is nowadays largely recognized as an indispensable resource in seismic hazard assessment (Faccioli, 2006).

ACKNOWLEDGMENTS

This work was supported primarily by the Portuguese Foundation for Science and Technology (FCT) through the Programme “Pluri-Annual” for “Centro de Geologia – Lisboa, U.I. 263, POCTI-ISFL-5-263”, co-financed by FEDER and “Centro de Geofísica – Lisboa, U.I. 170, POCTI-ISFL-5-170”, co-financed by FEDER.

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