A SOIL CLASSIFICATION FOR SEISMIC HAZARD ASSESSMENT AND MITIGATION OF THE ALGARVE

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ABSTRACT :

The Algarve province of Portugal is located near the E-W Eurasia-Africa plate boundary. It is characterized by a moderate seismicity, with some important historical earthquakes causing important damage and economical losses. Not only has it suffered the effects of large plate boundary events but also the impact of local onshore moderate-sized earthquake sources. The seismic hazard evaluation and mitigation of the area is therefore of great importance to the local populations and the large number of tourists that frequent the region. This paper focuses the evaluation of the most interesting and useful geotechnical near-surface parameters and a soil classification. The classification based upon the European Code 8 for civil engineering and SPT bedrock data, was carried out for land use planning and design of critical facilities. P-wave and S-wave seismic velocities were obtained through the acquisition, processing and interpretation refraction profiles. Hundreds of SPT parameters from available boreholes drilled for engineering and water supply were used and subsoil classification based on geophysical and geotechnical parameters is presented. Other parameters, such as Vp/Vs ratios and the Poisson coefficient were estimated and were computed to provide information for future site effect studies. The experimental procedure tested here is relatively fast, economical and easy to perform and can be useful to estimate soil microzoning and seismic hazard mapping in the absence of local earthquake records.

KEYWORDS: seismic hazard, seismic refraction, SPT, soil classification

1. INTRODUCTION

The study area (Fig. 1a), seems to be in a transitional state to a convergent plate boundary (Ribeiro et al. 1996; Ribeiro 2002). This tectonic setting is responsible for an important regional tectonic activity that produces a significant seismicity (Fig. 1b) and seismogenic potential (Dias 2001; Dias and Cabral 2002).). Historical and instrumental earthquakes have affected some of the major cities on the study area (Carrilho et al., 1997), causing damages and loss of lives.

Seismic zonation studies have identified three major seismogenic sources (Rio et al., 2006): Area A -including eastern onshore and offshore Algarve; Area B- a north-south trending low magnitude seismicity incorporating the Portimão fault; and Area C – an offshore zone SW of Cape S. Vicente responsible for strong events such as the famous Lisbon 1755 Earthquake. The probability of exceedance of an event of magnitude greater than 7 in 100 years is for areas A, B and C of 7%, 0.3% and 64%, respectively (Rio et al., 2006).

Site effect studies are extremely important, for which the geodynamical characterization of the shallow layers is required. Several methods exist to estimate site effects, which can be grouped into three main categories (Bard, 1997): 1) experimental, 2) numerical and 3) empirical. The first group_includes macroseismic observations, microtremors and weak and strong motion data. Numerical methods (2) depend on the availability of geotechnical information and more accurate and less limitative methods, based on 2D/3D wave propagation theory. Some site effects, which are known to influence ground motion such as topography and lateral discontinuities, are difficult to account with this methodology. However, these methods have provided a better understanding of site effects in the last 30 years (Bard, 1997).

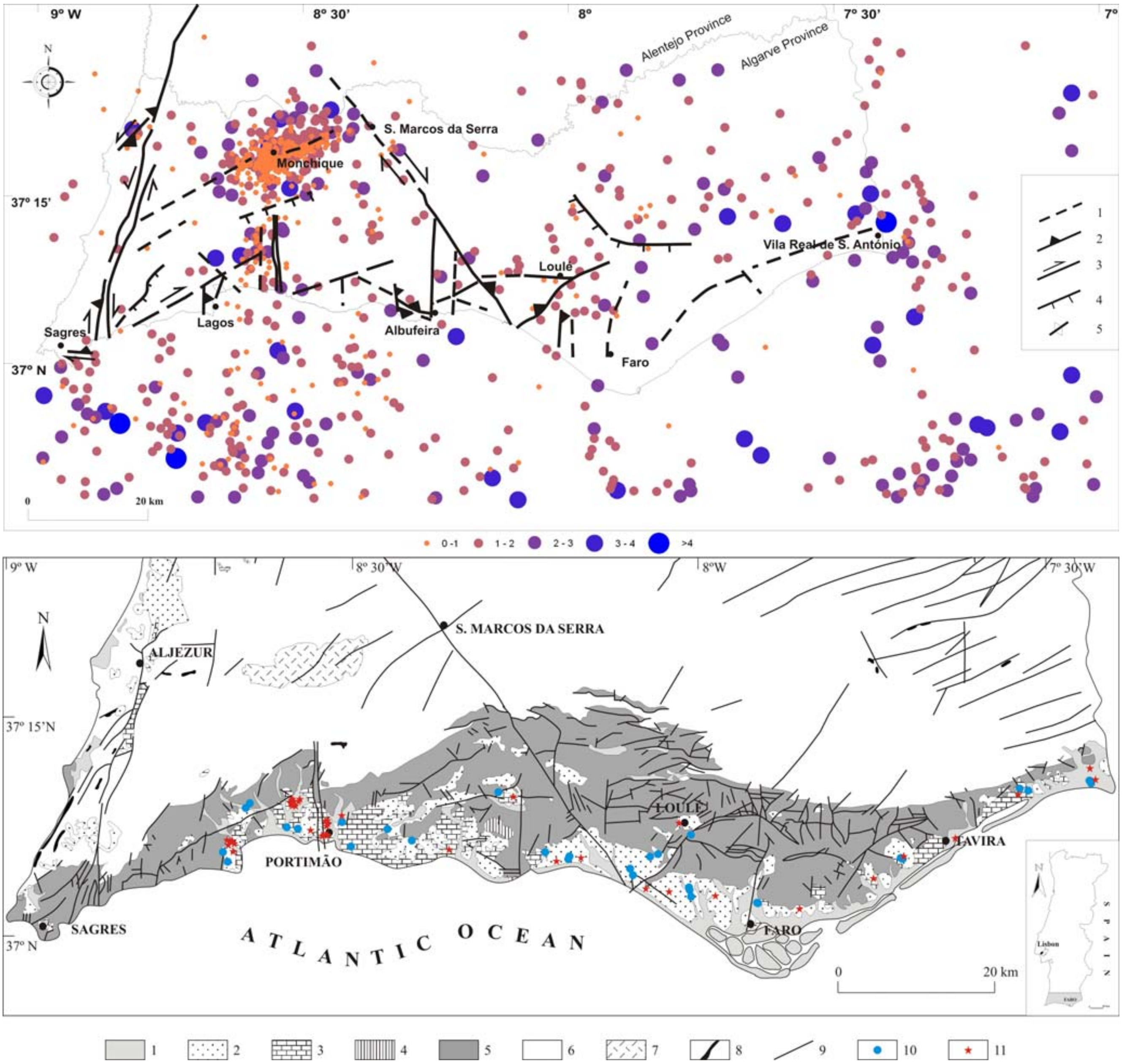

Figure 1. Top: a) Seismicity for the period 1961-2007 (source: Instituto de Meteorologia) and active faults (after Dias and Cabral 2002). Bottom: b) Study area location and schematic geological map of Algarve (adapted from Oliveira et al. 1992). The location of geotechnical soundings and seismic refraction profiles is also shown. 1- Quaternary; 2- Pliocene-Pleistocene; 3- Miocene; 4- Paleogene; 5- Mesozoic; 6- Paleozoic; 7- Monchique intrusive massif; 8- dyke; 9- fault; 10- geotechnical sounding; 11- seismic refraction profile.

The last grouping of methods (3) relies on relationships derived from earthquake motion and surface geology: i) Qualitative surface geology/seismic intensity increment correlation; ii) Surface geology/local amplification relationships; iii) Amplification/geotechnical parameters relations (shear-wave velocity and SPT – standard penetration test). Empirical attenuation laws correlate specific ground motion parameters (peak ground acceleration, velocity or displacement, e.g.) with the magnitude and distance of the seismic source. The relations often incorporate a crude site parameter, such as 1 for soils and 0 for hard rock (Penelis, 1997).

Near surface P and S-wave seismic velocities provide valuable information for studies of ground motion behaviour, natural frequencies and the liquefaction potential under earthquake (e.g. Bauer et al., 2001; Fumal and Tinsley, 1985). If macroseismic data or earthquake records are not available, this information is even more important to obtain the microzoning data and to estimate site effects. Several methods for estimating shear waves can be used, such as borehole logging, seismic refraction profiles or surface waves inversion.

The main objective of this work is to provide information about the geomechanical properties for the first ten meters of the subsurface, using P and S wave velocities from refraction studies and geotechnical information. Poisson's coefficients and V_P/V_S ratios were determined and a subsoil classification based on the Eurocode 8, was estimated from shear wave velocity, layer thickness and SPT information. Soil classifications are used for seismic action characterization and spectra design and can be directly used for defining the response spectra of a particular geographical area.

2. GEOLOGICAL SETTING

Outcropping in the northern area, the Paleozoic basement is intruded in northwestern Algarve, at Monchique, by an igneous intrusive massif of Upper Cretaceous age (Fig. 1b).Mesozoic and Cenozoic rocks can be found in two superposed sedimentary basins, in the South (Fig. 1b). A Cenozoic basin was formed by flexural processes associated with the collision of Africa and Iberia (Terrinha, 1998).

The Cenozoic deposits include yellow or pink massive and very fossiliferous biocalcarenites, (Lagos-Portimão Formation) of Lower-Middle Miocene age, overlaid by laminated sandstones poor in fossils of Upper Miocene age (Pais et al., 2000). The uppermost Miocene deposits are the Mem Martins spongoliths and the Cacela Formation (Antunes and Pais, 1993; Legoinha, 2003). The former comprises white spongoliths in angular unconformity over Cretaceous units, while the latter comprises conglomerates, fine sandstones and fine sands intercalated with levels of carbonate concretions (Cachão, 1995; Pais et al., 2000) overlying the Triassic sediments and the Lagos-Portimão Formation. Sands and sandstones of the Galvanas formation of Pliocene-Upper Miocene age (Antunes et al., 2000) occur at the centre of Algarve.

Pliocene sand deposits in association with marls, lacustrine limestones and a silty calcrete of the Morgadinho Deposits outcrop at the Morgadinho and Luz de Tavira areas. Pliocene to Pleistocene fluvio-deltaic reddish sands and conglomerates (Ludo Formation) overly the Paleozoic basement, the Mesozoic or the Miocene sediments (Manuppella, 1992; Moura and Boski, 1999). The Ludo Formation, which covers a very irregular karst surface, developed in the Mesozoic and Miocene carbonate rocks and is often affected by strong deformation produced by subsidence or sudden collapse (Dias and Cabral, 2002). In the Portimão and Loulé areas also outcrop gravels and sands of Pleistocene age (Odiáxere Gravels and Loulé Sands) (Dias, 2001). Associated with the fluvial drainage system occurs alluvium and terraces of Holocene age.

3. INFORMATION USED

3.1 Seismic refraction data acquisiton

Only Cenozoic terrains were studied since hard Mesozoic and Paleozoic formations are assumed to present a very low liquefaction susceptibility (Jorge, 1994; NRC, 1985, e.g.) and low site amplification (Borcherdt and Glassmoyer, 1992, e. g.). The location of the profiles was selected according to the geological, lithological information collected by an experienced geologist of the study area and the location of existing geotechnical soundings. All Tertiary formations were sampled at least once. A total of 24 locations were selected (Fig. 1b) and tests were conducted at two additional sites. Data are presented in Table 1.

In the S-wave records, strikes from the opposite side of the beam were usually summed with polarity reversal of one of the strikes, in order to eliminate P-wave contamination (Hasbrouck, 1991). For first arrival picking, strikes from both sides of the wooden beam were used and compared. SEG polarity convention is used, in which vertical impact produces a downswing in first arrivals for P wave surveys and for S wave profiles. The base of horizontal geophones for transverse strikes was oriented in the same direction of first one.

3.2 Geotechnical information

Hundreds of wells were drilled in the Algarve for water supply and geotechnical studies, performed for engineering purposes, covering almost all the geological formations of the study area (Hydrogeology Department of INETI). All this information was collected, geo-referenced and integrated in a GIS together with other geological and geophysical data.

SPT values were, when available, used to detect the basement depth on the seismic refraction profiles. In this paper, SPT values from 218 wells drilled in the study area Cenozoic formations were used (Table 2, Fig. 1b). Other wells with SPT data from Mesozoic and Paleozoic formations were also analysed, but, if the basement, defined as N parameter is >60, was reached close to the surface or at less than one meter, the data from these wells were not considered. Tests were performed every 1 or 2 m. The average and SPT extreme values found for each geological formation are presented in Table 2. When the basement was deeper than 10 m, SPT values were averaged only until this depth. Depths to the basement are also showed in the Table 2, where from simple analysis, a wide range of the N value for each geological formation is presented. The value of this parameter depends on the lithology being drilled but there is no linear relationship between the N value and the age and depth of the geological formation. The Lagos-Portimão and Ludo formations ares the geological units presenting the widest range of values due to the presence of different lithological units.

4. REFRACTION DATA INTERPRETATION AND APPLICATIONS

4.1 Refraction Data Interpretation

Interpretation of P and S wave refraction data was done by commercial software using the methods of Haeni et al. (1987) and by the Generalised Reciprocal Method (GRM, Palmer, 1980) combined with the intercept-slope method. The first method uses the delay-times method for a first model, followed by three iterations of raytracing and minimization by least squares of the residuals. Velocities were estimated by a weighted average (by the number of points used in the estimate) of a simple linear regression of the first arrival data and the velocity function from the GRM. Because the noise levels were generally low, the first arrival could be picked with an accuracy of ± 3 ms.

4.2 Application to the Estimation of Geomechanical Parameters

From the refraction surveys, seismic velocities and V_P/V_S ratios were calculated and from these, Poisson’s coefficient (σ). The velocities, V_P/V_S ratios and σ for each profile are shown in Table 4.1. In the first two layers, the shear wave velocities observed in the transverse receiver component range 108 m/s-1222 m/s, while compressional waves velocities, P, varies from 249 m/s to 2038 m/s. For the first layer, V_P/V_S ratios exhibit a range from 1.46 to 3.26 and for the second layer this ratio is from 1.47 to 7.0, while σ varies from 0.06 to 0.49 for the two layers.

Good conformity between P-wave and S-wave models was found when the water table was not very shallow (PN1, VRSA2 and Alv1, e.g., see Table 1). When this happens, the profiles present the highest V_P/V_S ratios and σ for both first and second layers. The determined values of V_P/V_S ratios and σ are consistent with those found in the literature for similar shallow sediments (Salem, 2000; Lankston, 1990).

The profiles PN1, VRSA2 and ALV1, e.g., present, for the second layer, higher values than those usually found for totally saturated shallow sediments (Salem, 2000; Lankston, 1990). Values of V_P/V_S ratios up to 9 however, have been several times reported in water-saturated, unconsolidated or clayish sediments (Salem, 2000).

Table 4.1 – Seismic velocities, Poisson' coefficient (σ) and V_P/V_S ratios for shallow layers calculated from refraction data.

Geology	Profile	Velocity (m/s) 1st Layer		VP1/VS1	σ1	Velocity (m/s) 2nd Layer		VP2/VS2	σ2
		P wave	S wave			P wave	S wave		
Alluvium	PN1	265	108	2.45	0.40	1902	301	6.32	0.49
	ALV1	541	166	3.26	0.45	2038	291	7.00	0.49
	VRSA2	225	117	1.92	0.31	1304	370	3.52	0.46
		120	60	2.00	0.33	1600	183	8.74	0.49
	TRAF15	173	95	1.82	0.28	1503	295	5.09	0.48
Sand dunes	VRSA1	275	162	1.70	0.24	2000	269	7.43	0.49
Loulé Sands	LOU17	111	90	1.23	-0.47	595	234	2.54	0.40
Odiáxere Gravels	OD1	325	188	1.73	0.25	1396	885	1.58	0.16
	FRA2	499	331	1.51	0.11	905	520	1.74	0.25
Ludo Formation	LG2	285	189	1.51	0.11	736	457	1.61	0.19
	LGA1	365	250	1.46	0.06	816	495	1.65	0.21
	POR1	529	307	1.72	0.25	826	472	1.75	0.26
	OLH11	612	499	1.23	-0.47	1254	573	2.19	0.37
	GAM13	363	310	1.17	-0.85	815	574	1.43	0.02
	ALB20	272	123	2.21	0.37	838	710	1.18	-0.77
	GAR21	311	266	1.17	-0.85	882	745	1.18	-0.77
Cacela Formation	CAC4	236	146	1.62	0.19	535	365	1.47	0.07
Mem Moniz Spongoliths	TUN1	255	111	2.30	0.38	724	340	2.13	0.36
Morgadinho Deposits		171	146	1.17	-0.85	620	428	1.45	0.05
Galvanas Formation		450	252	1.79	0.27	1085	687	1.58	0.17
Lagos-Portimão Formation	ALV2	249	113	2.20	0.37	1254	573	2.19	0.32
	ALB1	311	193	1.61	0.19	582	334	1.74	0.25
	LG1	365	179	2.04	0.34	1152	665	1.73	0.25
	FRA1	308	121	2.55	0.41	1795	1222	1.47	0.07

Table 4.2 – SPT values from the cenozoic units covering the Algarve (Sand dunes, Odiáxere Gravels and Morgadinho Deposits were not sampled). Basement is defined as N=60 at the 1rst phase or consecutive values of 60 at the 2nd phase.

Geology	Age	SPT (N value)		Depth to basement (m)		Number of wells
		End values	Average	End values	Average	
Alluvium	Holocene	3-33	19	6-38	17	57
Loulé sands	Pleistocene	19-60	42	0-9	3	3
Ludo Formation	Pliocene-Pleistocene	12-60	38	2-25	11	55
Galvanas Formation	Pliocene-U. Miocene	51-56	53	4	4	3
Mem Moniz Spongoliths	Upper Miocene	17-45	31	6.5-27	18	17
Cacela Formation	Upper Miocene	34-60	44	1-7	5	11
Lagos-Portimão Formation	Middle-Lower Miocene	8-60	25	0.5-31	12	72

4.3 Application to a Soil Classification

The construction of buildings and civil engineering structures have to be built in accordance with local subsoil classification established on the basis of the respective seismic risk (Penelis, 1997). From collected S-wave data and the reports from selected SPT, a classification of the gross soil dynamic properties was proposed considering for local characterisation of the geophysical and geotechnical sampled areas. Then, the coarse sampling was generalised using available digital geological cartography, in a GIS environment. It should be noted that what is represented as a single geotechnical sounding in Figure 1b is in fact a group of several jointly soundings within a more or less extensive area, general fairly representative of the geological formation areas.

Table 4.3.1 Classification criteria used in the soil classification.

CLASS	CRITERIA 1	CRITERIA 2
Subsoil class A	rock or geologic formation characterized by $V_s >= 800$ m/s	compact deposits of sands, gravels or overconsolidated clays, several tens of meters thick ($V_s >= 400$ m/s at 10 m depth)
Subsoil class B	deep deposits of medium dense sands, gravel or stiff clays with thickness from several tens to hundreds of meters ($V_s >= 200$ m/s at 10 m depth to $V_s >= 350$ m/s at 50m depth (SPT N~60)	
Subsoil class C	loose cohesionless deposits with or without soft cohesive layers ($V_s < 200$ m/s at depths <20m (SPT N<=10)	deposits with soft-to-medium stiff cohesive soils ($V_s < 200$ m/s at depths <20m (SPT N<=10)

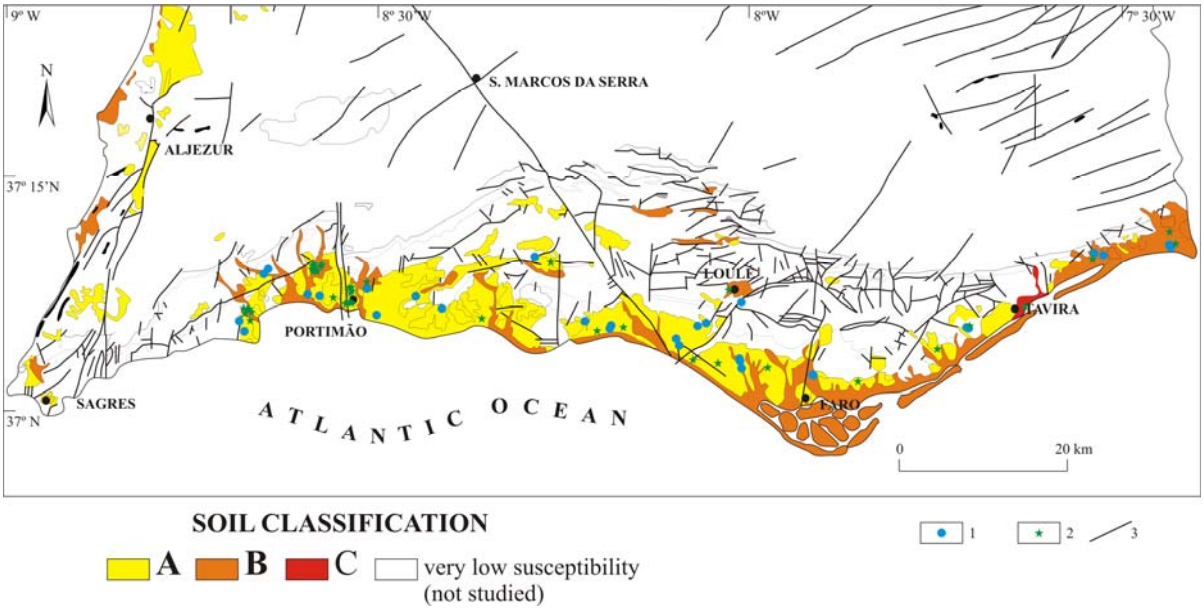

Figure 2 Soil classification map according to shear-wave velocity, layer thickness and SPT data. 1- Geotecnical sounding; 2- refraction profile; 3- faults and geological contours of Fig. 1b

So, the soil conditions are traduced by shear-wave velocity and layer thickness (Penelis, 1997). Due to problems in determining the bedrock with refraction studies (defined by seismic velocities over 2 km/s and 0.8 km/s for P wave and S Wave, respectively), SPT values were used, when available, to determine the presence of this unit. These SPT values are therefore included in the subsoil classification, but they were not included in the original classification presented by Penelis (1997). The classification criteria used are shown in Table 4.3.1. The geological cartography used ranged in scales from 1:50 000 to 1:500 000 and also from unpublished lithostratigraphic data of one of the authors at a finer scale. However, the results are presented here at the 1: 200.000 scale (Fig. 2).

5. DISCUSSION

The soil classification produced is presented in Figure 2. Subsoil class C were only found near Tavira. Mesozoic and Paleozoic formations were not studied due to a very low susceptibility of amplification or of liquefaction. P-wave velocities for the first layer obtained from many refraction profiles collected by the authors in Mesozoic and Paleozoic terrains in other areas are in the range 152-751 m/s. The average thickness surface layer varies from about 1 to 7 m. Using average V_P/V_S ratios for non-saturated formations in the Table 1, the maximum S-wave velocities for this layer is 417 m/s. Since bedrock P-wave velocities, under these profiles, are usually above 1500 m/s, these would place respective soils under class A. Since a great number of refraction profiles would be required to estimate their classification, the latter was not attempted.

Another important issue is the relationship between SPT and seismic velocities. There is no clear correlation between the estimated geomechanical parameters from seismic and SPT data (Carvalho et al., 2008). This lack of correlation is very probably due to the composition of different lithologies of each geological formation, presenting relatively wide range of the N values. Several conclusions can be deduced from data on Table 1: no apparent relationship between the N value and geological age exists; depth seems to produce a secondary effect on the N parameter; lithology is the most apparent factor for the former parameter.

The Lagos-Portimão Formation is a good example of this problem. Analysing the velocities found for this geological unit presented in Table 1 (ranging from 334 m/s to 1222 m/s) and the values of the N parameter, shown in Table 2 (ranges 8-60), are producing apparent anti-correlation between seismic and SPT parameters. These results agree with those of others (Thelen et al., 2006, e.g.), that conclude that shallow geology is not a good corollary for determining soil amplification factors (Lenz and Baise, in press).

6. CONCLUSIONS

In the absence of macroseismic data or earthquake records, the seismic refraction technique and SPT data are traditional and solid approaches of acquiring information for site effects and microzoning studies. Other methods for obtaining S-wave velocities, such as borehole logging or multichannel analysis of surface wave can also be applied. Here, P-wave and S-wave velocities were obtained from seismic refraction profiles acquired throughout Algarve, together with surface geology and SPT data, providing mechanical characterization of the geological formations of the area. Though the spatial sampling of the shear wave data was coarse and the depth of penetration was limited, the SPT data compensated for both problems and allowed the elaboration of useful subsoil classification.

This characterization was used not only to produce a subsoil classification in order to describe response spectra used to design seismic actions in earthquake engineering and, but also to estimate geomechanical parameters such as V_P/V_S ratios and Poisson coefficients, from which site effects and microzoning can be evaluated. This conclusion implies that a detailed geological cartography with lithological mapping should be used for proposing detailed microzoning and improved site effects studies.

Though a liquefaction potential map exists for the region based on geological criteria, for the first time a classification of the soils based on geophysical, geotechnical and geological data is produced in the Algarve and can be further refined in the future and combined and cross-checked with other types of data, such as soil response frequencies, which have been collected for the study area. To model local effects of ground motion amplification under an earthquake, V_P/V_S ratios and the Poisson coefficients are important parameters. Whether used directly to perform microzoning of the study area through empirical methods, or indirectly as input parameters in more sophisticated numerical methods, the data will improve this first microzoning of the Algarve. Used in conjunction with seismicity hazard data, such as peak ground accelerations and seismic intensities, it will constitute an important improvement in the seismic risk evaluation and mitigation in the study area and will provide important information in land use planning and civil protection management.

ACKNOWLEDGMENTS

The CAPSA project was supported by the Portuguese FCT and the E.U. and the ERSTA protocol by the ANPC. Our thanks to the Instituto de Meteorologia and F. Carrilho for supplying the seismicty data. The authors also thank J. Gomes & F. Caneiras.

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