EVALUATION OF SITE EFFECTS IN ADRA TOWN (SOUTHERN SPAIN).

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ABSTRACT

Recent destructive earthquakes have shown that damage distribution is generally related to soil typology, large differences being noticed in the level of damage for relatively short distances. In order to evaluate the site effects in Adra town (southern Spain), geological and geomorphological survey and microtremor measurements were carried out. The geologic materials have been classified according to their seismic amplification capacity. To achieve this goal, basic geological and geotechnical characteristics have been determined (N-values for the SPT tests and density), identifying the nature of the material and obtaining the calculated values of the S wave velocity (Vs). Measurements of short-period microtremors were performed in and around the town, and Nakamura's method was applied to determine a predominant period distribution map. The predominant period range is from 0.1s in rock site (northern part of the town) to more than 0.5s at soft soil site (southern part of the town). These results will be used in the evaluation of ground dynamic properties and will be included in seismic microzoning of Adra town.

1. INTRODUCTION

The concentration of human activity in urban areas implies an accumulation of risk elements, to which traditional seismic hazard studies do not devote enough attention. This is why specific studies based on very detailed research of close sources are essential, as are *in situ* measurements that take into account local effects. Priority has to be given to this sort of studies in order to prevent, mitigate and manage seismic risks.

The superficial geology of an urban area has a remarkable influence on the distribution of the damages caused by an earthquake. It has been proved that soil movement during an earthquake can be amplified by local landform conditions (e.g., Aki, 1993; Bard, 1999), and in some cases it amplifies the seismic shake in a range of periods that coincide with the period of vibration of the damaged structures (Seo, 1994), showing the relationship between the amplification caused by surface geology and the degree of destruction.

Even though urban geomorphology is a term that appeared only recently (Gutiérrez *et al*., 2001), its use has spread significantly over the last few years. The main reason is that a large number of areas that include town centres have been subject to land-planning studies that have included edaphological (e.g. Santos, F. and García, J.M., 1993; Marañés, *et al*. 1998; Aguilar *et a*l., 2000, 2002) and geomorphologic perspectives, linked to the prevention of natural risks and territorial divisions (e.g., Miralles, J.L. and Trenor, M., 1987; Galán *et al*., 1987; Matsuda *et al*., 1998; Alcalá-García *et al*., 2002). Geologic microzonation studies involve studying site effects. Although the site effect differs at each point and the capacity of estimating this phenomenon is limited, the research area can be divided into different areas that have almost homogeneous soil conditions, allowing us to estimate their response in the event of an earthquake. Dividing the research area into regions in line with material conditions is a very useful way of reducing the number of sites whose effect has to be considered. The first step will be the geological and geotechnical identification of the materials, after which the obtained soil conditions will be extrapolated.

Due to close relation between microtremors and the fundamental dynamic behaviour of the surface soil layer (Taga, 1993), microtremor measurements can prove a useful tool for evaluating the properties of earthquake ground motion and also for extrapolating the seismic motion observed at a given point to its surrounding area. In recent studies, ambient noise measurements have been widely applied for some purposes (Seo, 1994). The results obtained from the application of long period ambient noise measurements (e.g., Ohta *et al*., 1978; Yamanaka *et al*., 1993, 1994) allow a *grosso modo* estimation of site effects. Short period ambient noise measurements have been applied to a wide range of seismic settings (e.g., Morales *et al*., 1991, 1993; Lermo *et al*., 1993; Field and Jacob, 1993; Field *et al*., 1995; Seo, 1994). The H/V spectral ratio method (Nakamura, 1989) has been discussed at great length and proven to be a suitable, quick and effective method (Konno and Ohmachi, 1998; Bard, 1999; Enomoto *et al*., 2002) for determining the predominant period of soil. This method has been applied to different Spanish cities exposed to a moderate seismic hazard (Vidal *et al*., 1996; Seo, 1999; Pujades *et al*., 2000; Alfaro *et al*., 2001; Cheddadi, 2001; Navarro *et al*., 2001).

This paper presents the classification of the geologic materials obtained in the urban area of Adra town and puts forward a division based on the geological and geotechnical land conditions and microtremor measurements, for application in evaluating the town's seismic risk.

2. GEOLOGICAL SETTING

Adra town is situated in the SW of Almería province, in SE Spain (Fig. 1a). Geologically speaking, it is located inside the Alpujarride Complex, Internal Betic Zone (Sanz de Galdeano, 1997). The older materials form part of the Adra Unit (Alpujarride Complex), a group of metamorphic nappes constituted by Palaeozoic and Permo-Triassic phyllites, schist and micaschist (Sanz de Galdeano, 1997). These are covered by a layer of sediment that runs from the East to the West of the town, marking the Alpujarride bed-rock (Fig. 1b), and with complex geometries and spatial distributions (Fourniguet, 1975; Goy and Zazo, 1986). The Plio-Quaternary materials (Fig. 1b) are: deltaic facies (Middle Pliocene) formed by poorly rounded stone in a sandy-clayey matrix, which appear in the East of Adra town. The marine sediments (Pleistocene), formed by gravel and rounded pebbles fairly or very uncemented in a sandy matrix; the continental sediments constitute three generations of detrital glacis with red and fine silts, and gravel (Fourniguet, 1975; Goy and Zazo, 1986), fine sands in a red silty-clayey matrix, with little internal classification; and Holocene deposits consisting of a mixed alluvial-marine layer of fine sands and gravel, from 2 to 50 meters thick, and other alluvial deposits of the rain-fed watercourse that run through the town from North to South, and the recent marine terrace.

The 1:5000 scale map of studied area (Fig. 1c) has been obtained from borehole data and qualitative hydrogeological descriptions of some materials. 55 N-values have been included (where N corresponds to the number of blows necessary to sink the end of a conical probe 30 cm, applying a blow weight of 63.5 kg from a height of 76 cm) starting with 30 standard penetration tests (SPT) and 49 density values of the sediments (Table I).

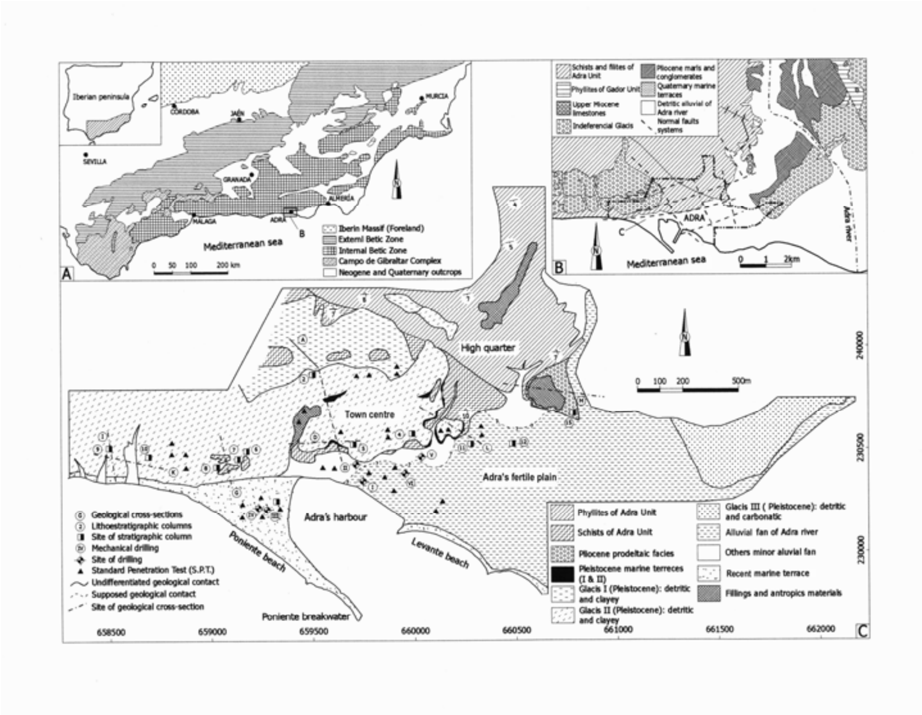

Figure 1. A: Geographical location of research area (Adra town, southern Spain); **B:** Geological description; **C:** Cartography of studied area to scale 1:5.000.

A first approach to the characteristic Vs of the materials has been obtained on the basis of the empiric calculation of the N-value (Table I), following the approaches of Imai (1981). This author relates the value of Vs with the N-value on the basis of the type of sedimentary formation. Vs will be similar to $102N^{0.292}$ in clayey alluvial, similar to $80.6N^{0.331}$ in sandy alluvial, similar to $114N^{0.294}$ in clayey colluviums and similar to $97.2N^{0.323}$ in sandy colluviums. Kokusho (1987) proposed another approach, where Vs will be similar to $80N^{1/3}$ for sandy materials and of $100N^{1/3}$ for clayey materials. The Vs values obtained (Table I) have been contrasted with the Vs values assigned to each geologic material according to several classifications. The first is proposed by the Spanish code NCSE-94 (Table II). The second considers SSD (Scenarios of Seismic Damages) studies used to classify the lands in families of similar properties before the dynamic excitement (Tiedemann, 1992). This methodology allows us to relate the seismic intensity to the ground-bearing capacity, characterized by the S wave velocity, and thus establish large number of types of material seismic response (Table II).

Characteristics of the materials								
Geological Formation	**Lithology**	**N-value (SPT) (average)(1)**	**Thickness (meters) (average)(2)**	**Density (gr/cm^3) (average)(1)**	**V_s by Imai (1981)**	**V_s by Kokusho (1987)**	**Underlying materials**	**Remarks**
Schist	Solid rock	>50 (>50)*	- - - -	- - - -	- - - -	- - - -	- - - -	More fractured and/or meteorized areas are vulnerable to landslides
Phyllites	Solid rock	- - - -	- - - -	- - - -	- - - -	- - - -	- - - -	Vulnerable to landslides
Pliocene conglomerate	Gravels with clayey matrix	>50 (>50)	>20 (5)	-1,90**	389	402	Solid rock	Vulnerable to landslides Non saturate material
Marine terraces 1 Marine terraces 2	Medium and gross sands	30-35 (32)	1-5 (2)	1,75-1,80 (1,86)	297	317	Solid rock	Vulnerable to landslides Very permeable semi-confined aquifer
Glacis 1 Glacis 2	Clayey sands and gravels	35-50 (41)	1-50 (12)	1,80-1,90 (1,86)	340	344	Marine terraces and solid rock	Capable of landslide Non-saturate material
Close alluvial	Medium gravels and sands	25-30 (27)	1-5 (2,5)	1,80-1,85 (1,82)	240	240	Solid rock	Vulnerable to liquefaction Very permeable free aquifer
Alluvial fan of Adra river	Fine limes and sands	15-20 (18)	1-5 (3,5)	1,85-1,90 (1,88)	266	262	Gross to fine sands	It is normally covered by fillings Vulnerable to liquefaction
	Medium gravels and sands	30-40 (34)	1-50 (22)	1,80-1,90 (1,83)	259	259	Pliocene and solid rock	Quite vulnerable to liquefaction Very permeable free aquifer
Recent marine terrace	Gross to fine sands	15-20 (17)	>15 (7)	1,75-1,85 (1,81)	205	205	Solid rock, Glacis 2, Terrace 2 and Adra river alluvial	Vulnerable to liquefaction Very permeable free aquifer
Fillings	Blocks and gravels	<10 (8)	Several (4)	<1,70 (1,65)	160	160	Several	Quite vulnerable to liquefaction Not very much solid materials

[1]The average values have been performed weighting 30 obtained measurements
[2]The average thickness on every layer has been carried out weighting the power of the stratigraphic columns and boreholes performed.
[*]In some fracture areas the N-values have been lower than 50.
[**]Estimated value according to the obtained value by these materials belonging to close areas.

Table 1. Geological, lithological and geothechnical decription of the lithological units of Adra town.

Table 2. Range of S-wave velocity and predominant period estimated of the materials present in Adra according to the geological and geotechnical characteristics.

Lithology	Landform NCSE-94 (1994)	Landform Tiedmann (1992)	V_s(m/s) Tiedmann (1992)	V_s(m/s) NCSE-94 (1994)	Thickness(m) Maximum[1] Average[2]	Predominant period ($T=4H/V_s$) Maximum[1] Average[2]
Solid rock	Type I	Type I	- 1000	> 750	---- ----	---- ----
Clayey gravels	Type II	Type II	500 - 1000	400 - 750	~ 20 5	~ 0,16 - 0,08 0,04 - 0,02
Medium gravels and sands	Type II	Type IV	- 500	400 - 750	50 12	~ 0,4 ~ 0,01
Gross and medium sands	Type III	Type V	250 - 500	< 400	5 2	0,08 – 0,04 0,032 – 0,016
Medium gravels and sands	Type III	Type V	250 - 500	< 400	5 2,5	0,08 – 0,04 0,04 – 0,02
Fine limes and sands	Type III	Type V	250 - 500	< 400	5 3,5	0,08 – 0,04 0,056 – 0,028
Medium gravels and sands					~ 50 22	0,8 – 0,4 0,352 – 0,176
Gross and medium sands	Type III	Type V	250 - 500	< 400	~ 15 7	0,24 – 0,12 0,112 – 0,056
Blocks and gravels	Type III	Type VI	100 - 250	< 400	10 4	0,4 –0,16 0,16 – 0,064

[1, 2]Range of maximum and average predominant period for the maximum and average thickness on every material.

The very thick deltaic alluvial materials saturated in water have an N-value from 15 to 20 and an average density of 1.78 gr/cm^3 (Table I), making them highly prone to amplify S waves during an earthquake (Seed *et al*., 1985). Their average Vs value (Table I) exceeds 250 m/s, equivalent to a Type V material, as classified by Tiedemann (1992). The marine terraces are just as prone, although their capacity to amplify the S waves is smaller (N-value between 30 and 35 and average density of 1.78 gr/cm^3). Their average Vs value is ~300 m/s, in agreement with the Vs values proposed by Tiedemann (1992).

The existence of several systems of conjugate fractures that affect the metamorphic bed-rock results in an N-value less than 50. There are alluvial materials overlying them (N-value between 25 and 30 and average density 1.82 gr/cm^3) and not very dense deltaic alluvial materials saturated in water, so these areas seem prone to seismic amplification. It has not been possible to determine their average Vs value, although it might be between 750 and 1000 m/s, according to the approaches proposed by NCSE-94 (1995) and Tiedemann (1992).

The glacis, significantly stable, is liable to amplify the S waves when their thickness exceeds 50 meters, as shown by its average N-value of 41 and their average density, 1,86 gr/cm^3. Their average Vs value is ~340 m/s, lower than the one proposed by Tiedemann (1992).

The heterometric deposits and recent marine terraces are the materials most liable to seismic amplification. These materials have a low N-value (<10 and 17, respectively), low density (<1,70 and 1,81 gr/cm^3) and a high water saturation rate. Their average Vs values are 160 and ~200 m/s, in good agreement with those described by Tiedemann (1992).

The predominant period of soil has been calculated theoretically by means of the expression $T = 4H/Vs$, where H is the soil thickness and Vs the S wave velocity. This relationship must be considered as associated to natural factors, such as the landform water saturation degree, but in general it usually gives good results (Towhaka and Roteix, 1988). Table II displays the range of maximum and average values of dominant periods for the different materials present in Adra town. These values have been obtained on the basis of the ranges of S wave velocity values proposed by Tiedemann (1992) and those obtained empirically from the relationships of Imai (1981) and Kokusho (1987).

3. MICROTREMOR OBSERVATIONS

There are several small amplitude vibrations that appear in a nearby surface ground. The period range of such vibrations is from 0.1 to 10 s. Vibrations that do not last long, less than 1 s, are currently called microtremors or Kanai's microtremors (Seo, 1994), and those that last longer are called microseisms (e.g. Taga, 1993). Microtremors are probably caused by vehicular traffic, heavy machinery, household appliances and other sources that are not related to earthquakes; however, there are small waves propagated from artificial sources associated to daily life. Kanai *et al*. (1954) originally introduced a theoretical interpretation and practical engineering application of microtremors that is especially convenient, easy and cheap for evaluating surface ground frequency properties. This has many engineering applications, for example, soil type classification of soil layers, prediction of ground shear-wave velocity and the evaluation of the predominant periods of soil layers during earthquake tremors.

Microtremor measurements in the town of Adra were performed in the summer of 1995 using two pairs of high-sensitivity seismometers, which have a natural period of 1 second, to record the horizontal and vertical components of microtremors at each site. After being integrated and amplified, the signal proportional to displacement was recorded directly on a lap-top computer. Microtremors were recorded at 160 sites with a 100m x 100m dimension grid (Fig. 3). Each observation time was 180 s and the signal was sampled every 0.01 seconds As microtremors spectra could be more or less influenced by close sources, Fourier spectra were calculated at each point for one or several parts of the vertical and the horizontal components records where there was no artificial disturbance. Consequently, we took special care to avoid disturbances caused by machinery, traffic or by pedestrians passing near the instrument during microtremor measurements, because such kinds of noise are transient and do not show the stationary characteristics of ground vibrations (Yamanaka *et al*, 1993). Therefore this part of the record was removed from the analysis or in the worst cases the measurement was repeated at the same point in more favourable conditions.

At each site, seven parts of the records were selected in order to conduct a Fourier analysis. The signal was Fourier transformed and smoothed using a 0.3 Hz Parzen's window. There were no significant differences in the two horizontal spectra, so they were geometrically averaged to generate a single horizontal spectrum (Yamanaka *et al*., 1994) and Nakamura´s method was applied obtaining the predominant period at each site.

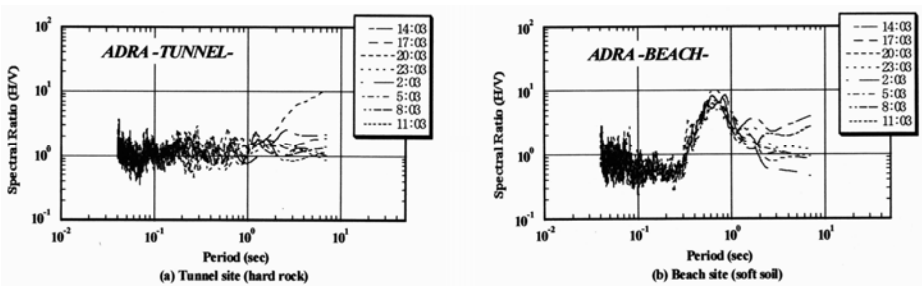

Figure 2. Continuous microtremor measurements for stationarity analysis.

In order to check the stationarity of microtremor measurements, continuous measurements were made for 24 hours at two sites with different soil conditions (Fig. 2). One site was located inside a tunnel (northern part of the town), with hard soil composed of schists and phyllites of Adra units. The other one was located in a beach area (southern part of the town), made up of Holocene alluvial fan deposit from Adra river. The H/V ratio obtained in the tunnel was very flat and the result obtained at the beach had very clear predominant peaks. These results show that H/V ratio is very stable. Finally, a map showing the predominant period distribution was prospected (Fig. 3). The predominant period values obtained vary from 0.1 s in the rock site (northern part of the town), thin Pleistocene materials and Holocene sediment (middle of the town) to more than 0.5 s in the southern part of the town, formed by alluvial fan deposit from Adra river. In general, the long period zone corresponds to the soft soil zone, with shorter periods in the hard and middle soil zones. In some places, long periods have been detected in the hard soil zone, this being due to local artificial deposits caused by farming or the filling of gullies and slopes.

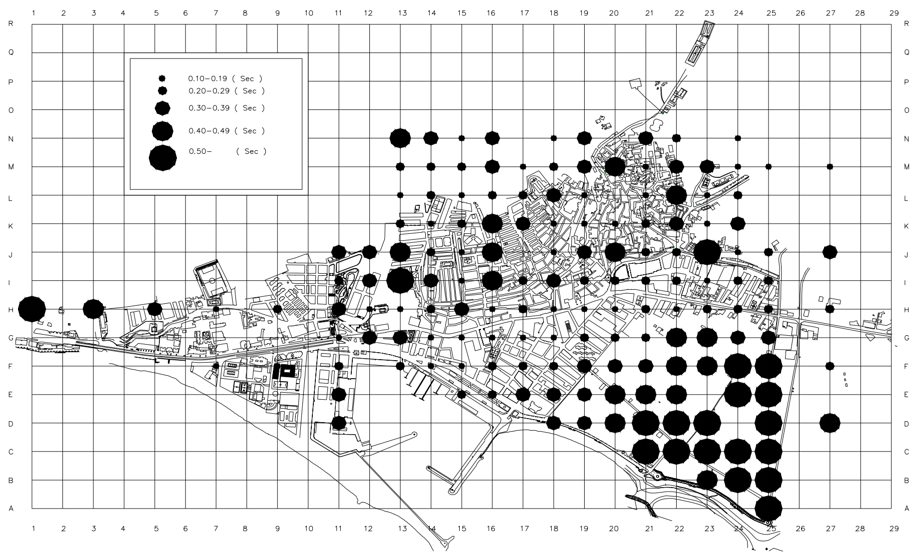

Figure 3. Predominant period distribution map in Adra town from microtremor data analysis.

4. DISCUSSION AND CONCLUSIONS

Accurate assessment of urban seismic hazards requires specific studies in which the differential effect of the soil has to be considered. This is known as seismic microzonation, and the main goal is to determine the surface response due to seismic excitation for each type of soil. The results serve to estimate the distribution of seismic intensities in future earthquakes for efficient risk management purposes, and also to define the seismic conditions required for the urban territorial distribution of the area.

The results obtained from the geotechnical description of the lithological units in Adra town are in good agreement with the field observations and interpretation models used (Table I and Table II). Furthermore, the glacis and Pliocene clayey conglomerates have empiric Vs values inferior to 400 m/s, according to the relationships of Imai (1981) and Kokusho (1987), and therefore smaller than those proposed by Tiedemann (1992) and NCSE-94 (1995). This discrepancy is related to the presence of interstitial water in its matrix, which is not considered in the approaches used.

The distribution of facies and geotechnical characteristics of the surface materials have been used to classify them, as a function of the likelihood of S wave amplification, giving a range of Vs values from ~160 to ~400 m/s. These results suggest that the materials are likely to amplify the S waves, the most likely being those with values below 250 m/s and low densities (fillings, present marine terraces and Holocene alluvium).

The predominant period distribution of soil, obtained by Nakamura's method, is clearly related with the subsurface soil conditions in Adra town and the predominant period values, obtained empirically from microtremor measurements, show good agreement with the predominant period calculated theoretically by means of $T = 4H/Vs$. These results prove that Nakamura's method is successful in identifying the fundamental resonant frequency of soil, a very relevant datum for the assessment of local site effects.

Using the results obtained in this study, we have plotted a preliminary seismic microzoning map of Adra town (Fig. 4), establishing 6 types of soil conditions. The proposed division in based not only on space and vertical distribution of the materials, but also on their water saturation degree and dynamic properties. Four types of materials with especially high predominant period values have been observed. The Holocene detrital alluvium of the Adra river, the anthropic deposits (fillings, smaller paved water courses, etc.), the recent marine terraces, and the continental glacis, which are more than 50 meters thick, would pose the most unfavourable soil conditions in the face of a seismic event.

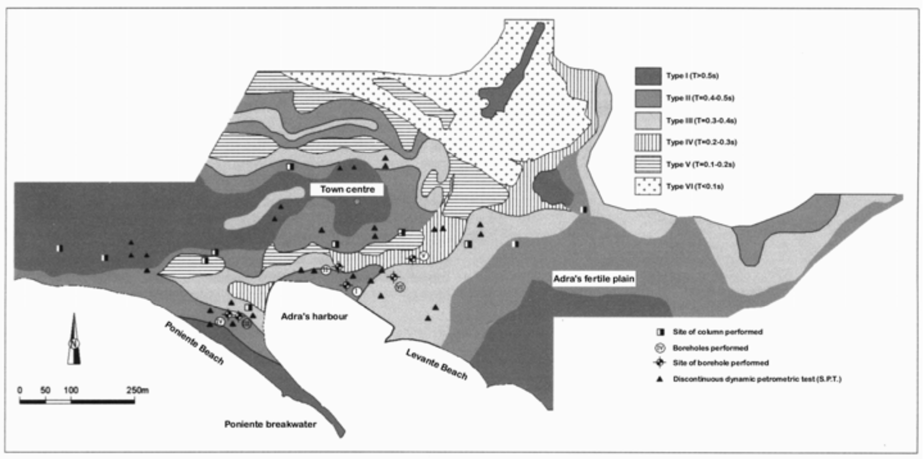

Figure 4. Cartographic classification of site effects in Adra town.

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