Far-field effects of the 1755 Lisbon earthquake in Catalonia, Spain. Influence of local geology and comparison with 20th century macroseismic data

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ABSTRACT

Investigation of historical sources reporting far-field effects on Catalonia, Spain, for the 1 November 1755 Lisbon earthquake was carried out (López et al., 1994). The effects described were mainly oscillations of water in water tanks and pools, oscillation of lamps and perception of ground and building motion. Non-perception in some towns and villages was also explicitly reported.

Correlation between these effects and local geological conditions is analyzed together with other macroseismic data for earthquakes in the study area during the 20th century. Differences on the behavior of a distant earthquake such as that of 1755 (low frequency ground motion) and moderate intensity local events (high frequency ground motion) are studied.

INTRODUCTION

A large amount of literature related to the historical 1755 Lisbon earthquake was written in the next years following the event, as the great damage produced in an important European town shocked the entire European society. A large number of reports on this earthquake is available; the number of references is copious but also heterogeneous: not only seismic reports but also philosophical and scientific discussions, religious explanations and even poetry (Muñoz and Udías, 1982; Roca et al., 2004; Martínez-Solares, 2001).

The first seismic catalogue referring the possible perception of the Lisbon earthquake in Catalonia was that of Perrey (1847), which absolutely stated that the earthquake was not felt. This statement is an evidence of the fact that he ignored the survey and resulting report drived by Ricardo Wall, Spanish minister of state of king Ferdinand VI, that is preserved at the *Archivo Histórico Nacional*, in Madrid (documents 1 and 2 in the Documentary Sources section). The catalogue of Fontserè and Iglésies (1971), a basic publication for the knowledge of the seismic history of Catalonia, also ignored these documents. Nevertheless, some years before, a study by Guillén (1956) had used these sources to draw a map of localities having suffered damage (none of these localities in Catalonia) and having felt the shaking (only 4 localities in Catalonia). Martínez Solares et al. (1979) used the document no. 2 to draw the isoseismal map of the earthquake. Rodríguez de la Torre (1985) also presented his interpretation of these sources for some localities in two areas of Catalonia (Girona and Maresme).

López et al. (1994) carried out an analysis of the results of the survey in the original document (no. 1) and the report (no. 2) together with other local documentary sources. As a result of their analysis, a listing of effects reported in 51 localities in Catalonia was presented. They specified five categories of effects, namely: A, oscillations in water reservoirs, pools and tanks; L, oscillations of lamps, mainly in churches; S, felt vibration; N, non felt (explicitly mentioned); and, F, effects in water sources as spring breaks, turbidity increase and water coloring. No damage was observed in any of the reported localities, as expected given that the epicentral distance is larger than thousand km.

Roughly comparing the geographical distribution of these effects –except for those classified as F) with a geological map of the region López et al. (1994) concluded that in general the oscillations tend to appear in the more recent, less consolidated materials while the absence of shaking (N) tend to occurred on ancient formations

In this paper the effects of the 1755 Lisbon earthquake in Catalonia reported by López et al. (1994) are re-analyzed, using a more systematic site classification and they are compared with macroseismic observations in the study area for more recent local events.

GEOLOGICAL SITE CLASSIFICATION

In order to prepare the earthquake emergency plan for Catalonia, SISMICAT (DGEiSC, 2003) a risk assessment at regional scale and a system to generate damage scenarios were carried out (Susagna et al., 2005). Site conditions for these evaluations had to be taken into account in a simplified way, following a methodology developed by Fleta et al. (1998) which characterized the main urban nucleus of each municipality of the study region using available geological maps at different scales; the geotechnical site classification is then based in the predominant surface geology using the four following classes (Bard et al., 1995):

- R: Rocky, unweathered rock and hard; shear wave velocity higher than 800 m/s; very good mechanical characteristics. Fresh rock.
- A: Granular, compact material; and cohesive hard clay or marl; shear wave velocity between 800-400 m/s; good to very good mechanical characteristics. Compact sands and gravels, highly consolidated stiff clays.
- B: Weathered or fractured rock; granular, semi-compact material; cohesive, semi-compact material and soft chalk; shear wave velocity between 400-150 m/s; average mechanical characteristics. Relatively compact sands and gravels, mean stiff marls and clays.
- C: Granular, non-cohesive material; cohesive soft clay, mud and weathered chalk; shear wave velocity lesser than 150 m/s; poor mechanical characteristics. Softs sands or gravels and clays, altered gypsum and muds.

In the earthquake emergency plan, on the basis of this classification, the intensities assigned to each municipality according to the hazard assessment (for medium rock site) were modified in the following way: for classes R and A no amplification was considered and for classes B and C an increase of half degree in the MSK intensity values was adopted.

In the present study, a more detailed analysis of the sites reported by López et al. (1994) having experimented effects for the 1755 Lisbon earthquake has been carried out. First, the geotechnical classification of surface formations, following the methodology developed by Fleta et al. (1998) has been re-evaluated taking into account in some extend the location of the urban nucleus or referred site at the time of occurrence of the earthquake. And, second, the depth of the basement –the surface of the permotriasic erosion (Fleta et al., 2006)– is considered.

In Table 1 the results of this site re-evaluation for the localities reported by López et al. (1994) are given: the column *Class_pre* gives the geotechnical class of the municipality were the site is located according to the previous classification by Fleta et al. (1998); in the next column of the Table (*Class*) the new site characterization is given; last column (*DB*) gives the approximate depth of the basement at the site.

DISTRIBUTION OF MACROSEISMIC EFFECTS OF THE 1755 LISBON EARTHQUAKE IN CATALONIA

The effects reported by López et al. (1994) for the 1755 Lisbon earthquake are presented also in Table 1 and are plotted in Figure 1, on a geological sketch of the study area.

TABLE 1. Reported effects of the 1755 earthquake in Catalonia and site classification. Legend: Macroseismic effects (1 equal at yes): E_A, Oscillations in water reservoirs, E_L, Lamps motion, E_S, Vibrations, E_N, Non felt (explicitely reported); E_F, Springs breaks; Class_pre, previous geotechnical classification given to the municipality by Fleta et al. (1998); Class, reviewed classification; DB, Approximate basement depth in meters.

Location	Municipality	E_A	E_L	E_S	E_N	E_F	Class_pre	Class	DB
Albanyà	Albanyà					1	B	B	-250
Albinyana	Albinyana	1					Rock	Rock	-500
Arenys de Mar	Arenys de Mar			1			C	C	<50
Barcelona	Barcelona			1			B	B	-90
Baronia de Rialb	Baronia de Rialb					1	A	A	-2600
Banyeres del Penedès	Banyeres del Penedès		1				A	A	-1300
Besalú	Besalú				1		B	B	-1000
Beuda	Beuda					1	C	B	-1400
Bruc	Bruc	1					B	B	<50
Caldes de Malavella	Caldes de Malavella			1		1	B	B	<50
Camprodon	Camprodon				1		B	B	<50
Canet de Mar	Canet de Mar			1			C	C	<50
Centelles	Centelles		1				B	B	-50
Cervera	Cervera		1	1			Rock	B	-1400
Collbató	Collbató	1					Rock	A	<50
Esparreguera	Esparreguera	1				1	A	B	-2800
Ribes de Freser	Ribes de Freser					1	B	C	<50
Gaver	Estaràs					1	B	A	-1400
Girona	Girona				1		B	A	<50
Hostalric	Hostalric		1				Rock	A	0
Gelida	Gelida	1	1			1	A	A	-100
Lleida	Lleida		1				A	A	-850
Maiα de Montcal	Maià de Montcal					1	A	B	-1250
Manresa	Manresa	1				1	Rock	A	-500
La Manresana	Sant Ramon	1					A	A	-1600
Masquefa	Masquefa	1					A	B	-1750
Mataró	Mataró				1		B	B	<50
Molló	Molló					1	Rock	Rock	0
Monistrol de Montserrat	Monistrol de Montserrat		1			1	Rock	Rock	-350
Montserrat	Monistrol de Montserrat	1	1				Rock	Rock	-800
Moiα	Moiα	1	1			1	Rock	A	-700
Mura	Mura					1	Rock	A	-450
Palafrugell	Palafrugell				1		A	B	<50
Puigcerdà	Puigcerdà			1			A	A	-600
Queralbs	Queralbs					1	Rock	A	0
Rodonyà	Rodonyà		1				B	A	-100
S'Agaró	Sant Feliu de Guíxols					1	Rock	Rock	<50
Sant Feliu de Guíxols	Sant Feliu de Guíxols			1			A	B	<50
Sant Pere de Riudebitlles	Sant Pere de Riudebitlles	1	1				A	B	-2250
Santa Coloma de Farners	Santa Coloma de Farners				1		A	B	-150
Sallent	Sallent					1	A	B	-750
Surroca	Ogassa					1	Rock	Rock	-600
Talamanca	Talamanca					1	Rock	Rock	-500
Talarn	Talarn				1		Rock	A	-4500
Tarragona	Tarragona						B	A	-1600
Terrassola	Torrelavit		1				A	B	-1300
Vallfogona de Ripollès	Vallfogona de Ripollès					1	B	A	-800
Vielha	Vielha				1		C	C	<50
Viladrau	Viladrau					1	Rock	Rock	0
Vic	Vic		1			1	B	B	-250
Vilanova de la Muga	Perelada		1	1			A	B	-500

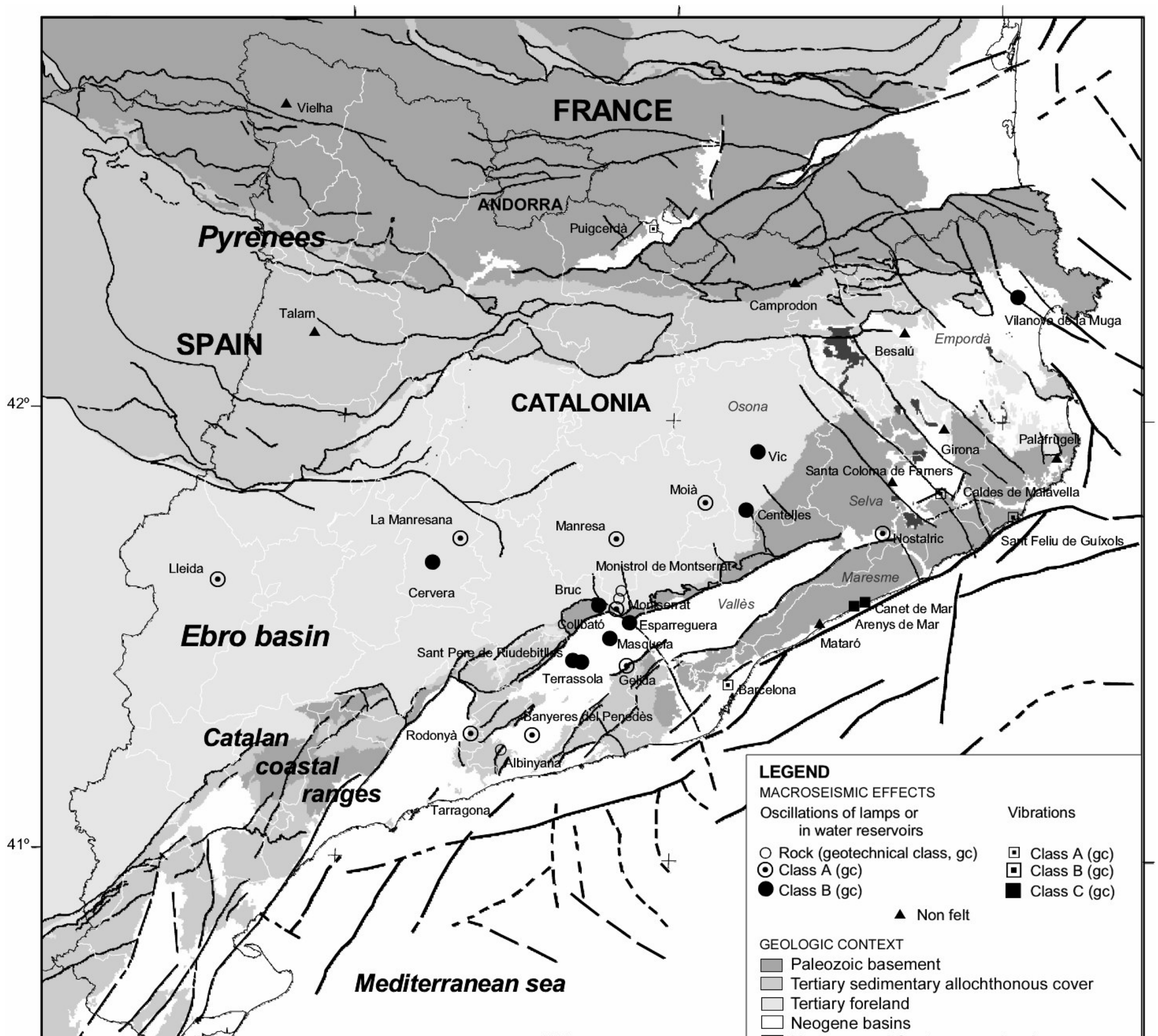

Fig. 1. Locations with described effects of the 1755 Lisbon earthquake on the geological context of Catalonia.

In this map (Fig. 1) it can be observed that most of the reported effects – oscillations of lamps and of water in reservoirs - occur at the localities located in the neogene basins (Catalan coastal ranges) and in the eastern margin of the Ebro basin.

In Table 2 it is presented the number of localities with macroseismic effects distributed according to their geotechnical class for basement depth equal or greater than 50 m and lower than 50 m.

TABLE 2. Distribution of the macroseismic effect according to geotechnical classes (Rock, A, B and C Classes) considering the basement depth (lower o higher than 50 m). L, lamps motion; A, oscillations in water reservoirs; S, felt vibration; N, non felt.

Effect	DB>=50m Geotechnic class				DB <50m Geotechnic class			
	Rock	A	B	C	Rock	A	B	C
L	2	5	6	0	0	1	0	0
A	2	4	3	0	0	1	1	0
S	0	1	3	0	0	0	2	2
N	0	1	2	0	0	1	3	1

Lamp oscillations (L) and oscillation of water in reservoirs (A), which can be considered as low frequency effects, mainly occur in localities with larger basement depth, even on geotechnical class R (“rock”) but mainly on soils (classes A and B). Felt vibration (S), effect that can be considered both as low or high frequency, is observed on areas of both high or low basement depth; in fact, four localities with felt ground motion are located on sites classified B or C with basement depth lower than 50 m and four on A or B sites with higher basement depth. Felt vibration (S) was never reported on rock sites.

INFLUENCE OF LOCAL GEOLOGY ON THE 20TH AND 21ST CENTURY MACROSEISMIC DATA

In order to analyse the relation between observed intensities in Catalonia for earthquakes occurred in the last hundred years and site conditions, searching for possible soil amplifications, macroseismic data from the 6 events listed in Table 3 are used. These events are selected to cover the areas where seismic activity is higher. The epicentres of these earthquakes are shown in Figure 2.

TABLE 3: Coordinates of epicentre and epicentral intensity of the earthquakes studied to evaluate soil amplification.

Earthquake	Epicenter	Latitude (N)	Longitude (E)	Io
23/10/17	Mediterranean sea	41º12'00"	2º18'00"	VI-VII
19/11/23	Vielha	42º40'00"	0º42'00"	VIII
12/03/27	Sant Celoni	41º42'24"	2º28'00"	VII
28/11/28	Mediterranean sea	41º27'00"	2º28'00"	VI
18/02/96	Sant Pau de Fenollet	42º47'24"	2º32'24"	VI
21/09/04	Queralbs	42º20'24"	2º10'12"	V

For all these events intensity data points are available. The method used to investigate soil effects consists of grouping in zones the data points that are located at similar distance and azimuth relative to the epicentre, in order to eliminate the attenuation effect, and computing a mean intensity value I_m for each of these zones. Then variations on the values of individual intensities I_i of localities in a given zone in relation to I_m for this zone are identified. It is then investigated if the differences I_i - I_m can be interpreted as soil amplification effect.

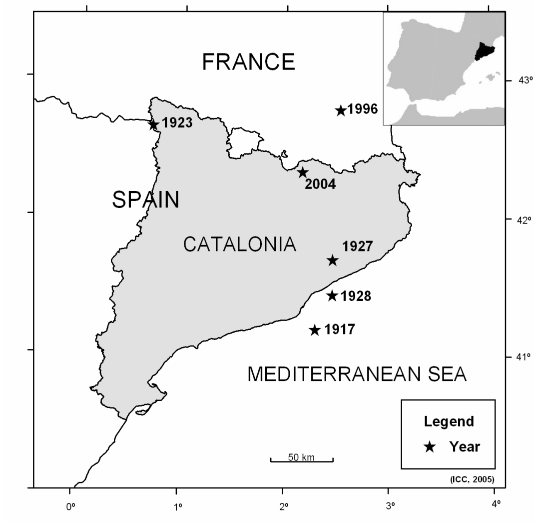

Fig. 2: Earthquakes analysed to investigate soil effects.

The regions with a larger number of intensity data points available for a larger number of events have been studied. This represents a number of 120 municipalities that are classified according their behaviour in 4 types:

- Type 1: Municipalities that mostly follow the behaviour “expected” according their geotechnical classification (R and A sites without amplification and B and C sites with amplification).
- Type 2: Municipalities that mostly do not follow the expected behaviour.
- Type 3: Municipalities that do not present a clear tendency; in some cases the expected behaviour is followed and in some cases do not.
- Type 4: Municipalities that are classified as R and A classes (rock and highly consolidated sediments) and where a decrease of intensity is often observed.

Figure 3 shows the geographical distribution of the considered municipalities, which are those of five *comarques* (administrative division comprising a number of municipalities): Osona, La Selva, Maresme, Vallès Oriental and Vallès Occidental. The results according the above defined behaviour type are shown in the Figure. The results are as follow: 30% of municipalities follow the “expected” behaviour (Type 1), while 37% do not follow it (Type 2); 20% of municipalities do not present a clear tendency (Type 3) and 13% show a deamplification in hard soils or rock sites.

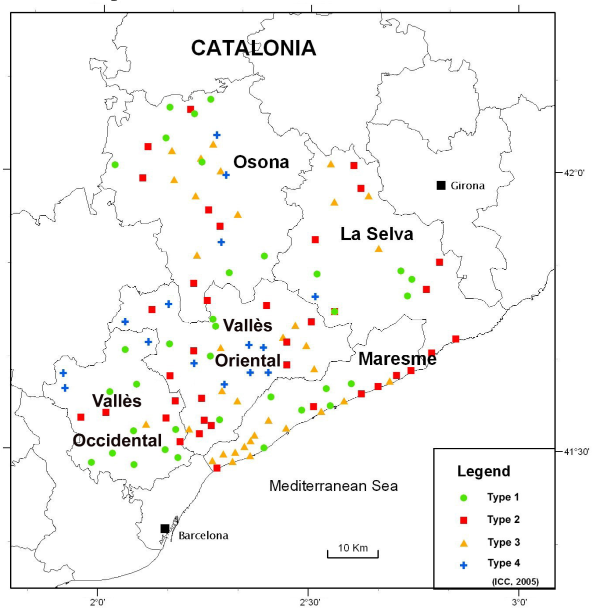

Fig. 3: Geographical distribution of considered sites (municipalities) showing their behaviour type.

The distribution of observed behaviour types of municipalities into soil classes is presented in Table 4. From this table the following facts can be pointed out:

- Class R municipalities do not present a clear behaviour
- In Class A sites some deamplification occurs (in 40% of municipalities)
- Class B labelled municipalities show a tendency not to experiment amplification (53% of Type 2)
- Class C municipalities show a tendency to experiment amplification (42%)

Thus, from this data set, not significant amplification would be predicted in the municipalities assigned as B according to the geotechnical classification.

TABLE 4: Behaviour type versus Soil Class.

Soil class \ Type	1	2	3	4
R	31%	31%	36%	2%
A	16%	30%	13%	40%
B	36%	53%	11%	-
C	42%	31%	26%	-

Comparison of the effects of the 1755 Lisbon earthquake with those observed in 20th and 21st century local earthquakes

In this section, we consider the municipalities for which reports on the effects of the Lisbon, 1755 earthquake were available to make a comparison with the above analyzed macroseismic effects of more recent local earthquakes.

The depth of the basement in each data point needs to be considered for this comparison as it strongly conditions the observed effects. Deep basement areas should have a tendency of amplifying in particular low frequency waves, as those reaching the region in the distant 1755 Lisbon earthquake, while shallower basements would not amplify those low frequencies but rather higher frequency waves generated by local events as those considered here from the XX and XXI century.

Figure 4 show the comparison of the sites reported for the 1755 earthquake that have enough data available for the 20th and 21st century events. For each site the effect described in the reports of the Lisbon earthquake is symbolized together with the corresponding Type of behaviour assigned to its municipality in the former section. In all of these points an increase of the ground motion should be expected, except for those points indicated in the map, Puigcerdà and Girona, where no amplification should be expected according to their soil class (A).

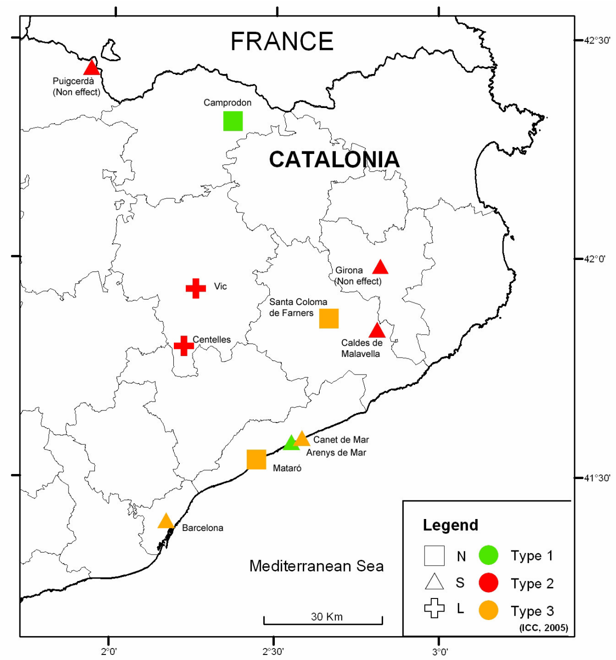

Fig. 4: Points (municipalities) where it is available both information on effects of the Lisbon 1755 earthquake and macroseismic data for the XX and XXI century events. For 1755 observations: N, not felt; S, felt vibration; L, oscillation of lamps. Type of behaviour for XX and XXI century macroseismic data: Type1: follows "expected" behaviour; Type 2: do not follow expected behaviour; Type 3: non clear behaviour.

No analogous behaviour is found comparing the effects of the 1755 earthquake with the "Type of behaviour" defined from more recent macroseismic data. For example, in the localities of Centelles and Vic (both on geotechnical class B and relatively deep basement) the 1755 earthquake was felt while no amplification of more recent events has been observed. However, in Camprodon (also geotechnical class B but with shallower basement) amplification is produced for recent events but the Lisbon earthquake was not felt. In Arenys de Mar (shallow basement but geotechnical Class C) experiments amplification for local events and the Lisbon earthquake was also felt.

In fact these observations, even if they are scarce, seem to indicate that amplifications in local, low magnitude, events (high frequency content of ground motion) are more related to the geotechnical class of shallow sediments while the presence of deep basement, independently of the soil characteristics, produces amplification of the very low frequency waves of a big distant earthquake as that of 1755.

Conclusions

Reported effects for the 1755 Lisbon earthquake in Catalonia have been investigated together with macroseismic data of more recent local events and geological and geotechnical site information.

Effects of this distant earthquake, which should have produced very low frequency waves, are mainly related to the deepness of the basement.

On the other hand, effects produced by local events seem to be more related to the geotechnical characteristics of the uppermost ground levels.

In order to go farther in this study, more macroseismic data for local events would be needed. These are not available due to the moderate seismicity level of the region in the last centuries.

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