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ORIGINAL RESEARCH PAPER

A new seismic hazard assessment in the region of Andalusia (Southern Spain)

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Abstract A probabilistic seismic hazard assessment of Andalusia (Southern Spain) in terms of peak ground acceleration, PGA, and spectral accelerations, SA(T), is presented in this paper. In contrast to most of the previous studies in the region, which were performed for PGA, making use of Intensity-to-PGA relationships, hazard was here calculated in terms of magnitude, using published spectral ground-motion models. Moreover, we considered different ground-motion models for the Atlantic sources, since the attenuation of those motions seems to be slower, as evidenced in the case of the extensive macroseismic areas of earthquakes like those occurred in the years 1755, 1969 and 2007. A comprehensive review of the seismic catalogue and of the seismogenic models proposed for the region was carried out, including those for Northern Africa, which is part of the influence area. Hazard calculations were performed following the Probabilistic Seismic Hazard Assessment (PSHA) methodology using a logic tree, which accounts for six different seismic source zonings and five different ground-motion attenuation relationships. Hazard maps in terms of PGA and SA (0.2 s) and SA (1 s) and coefficient of variation (COV) maps, for the 475-year return period were first obtained in rock sites. A geotechnical classification and amplification factors were proposed and new hazard maps including local effects were represented, showing PGA values ranging from 24 to 370 cm/s^2 for the whole Andalusian territory, with the highest expected values (PGA $>$ 300 cm/s^2) in some parts of the Granada Province and in the town of Vélez Málaga. Lowest values (PGA $<$ 50 cm/s^2) correspond to some towns of the Huelva

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and Córdoba provinces. The inclusion of soil effects provides a more detailed picture of the actual hazard the region is subjected to.

Keywords PSHA · Logic tree · Site effects · PGA · Spectral acceleration · Spain

1 Introduction

Andalusia, located in Southern Spain, is deemed to be a moderate seismic area in a worldwide context, but it is one of the Spanish regions with the highest seismic activity. For this reason, many seismic hazard studies have been focused on this region. Damaging earthquakes have struck the region several times in the last hundreds of years. Among them, the earthquakes occurred in December 25th, 1884 in Arenas del Rey (I_{EMS} = IX-X) and in September 22th, 1522 in the Gulf of Almería (I_{EMS} = IX) are noteworthy (hereafter, we denote the epicentral intensity in the European Macroseismic Scale EMS-98 by I_{EMS}). In the last 20 years some earthquakes with magnitude $M_w \sim 5$ took place, causing some damages and fear in the population, like the ones occurred in December 12th, 1989 in Ayamonte (Huelva), December 23th, 1993 in Berja (Almería), January 4th, 1994 in Adra (Almería) and February 4th, 2002 in Gérgal (Almería). Consequently, regional authorities have promoted a seismic risk assessment of Andalusia aimed at defining the emergency plans, which has been named the SISMOSAN Project (Benito et al. 2007). The first part of the project is a seismic hazard analysis, which is presented in this paper.

The seismic hazard assessment of moderate seismic areas is hindered by many factors. The limited availability of instrumental data of significant seismic series is one of the most important factors due to the lack of strong-motion models covering magnitude ranges of engineering interest ($M_w > 5.0$; e.g., Benito and Gaspar-Escribano 2007). The difficulties in characterizing seismic sources are also worth mentioning. To overcome these shortcomings, different authors have strongly based their studies on the historical seismic record of Southern Spain. No logic tree formalism for quantification of uncertainties was included in these studies.

This paper presents a new probabilistic seismic hazard assessment of the Andalusian region, accounting for epistemic uncertainties in seismic source definition and ground-motion attenuation by means of a logic tree. Two important peculiarities of the study are underlined. First, we considered special strong motion models for the Atlantic earthquakes (Azores-Gibraltar zone), taking into account the slower attenuation observed in this zone compared with the Mediterranean or continental shocks. The adopted models have been checked with local data of recent earthquakes. Second, we followed a regional approach to include site-effects in the seismic hazard estimations. As a result of the study we developed in a first phase the hazard maps for rock conditions for the 475-year return period in a wide range of spectral ordinates to be used in subsequent phases of the SISMOSAN Project. In a second step, the hazard maps considering soil conditions were presented. This is the first time that seismic parameters of expected ground motion [PGA and SA(T)] have been obtained for the region of Andalusia including the influence of shallow ground structure on the shaking strength. These last maps show the real hazard affecting the entire region in a more realistic way.

2 Previous seismic hazard studies in Andalusia

The first seismic hazard studies of Andalusia were carried out during the 1960s, when accelerometric stations did not exist yet and the macroseismic intensity was the only parameter representative of the motion. Hence, seismic hazard maps in terms of macroseismic intensity

were obtained following a deterministic approach by Munuera (1969), thus laying down the groundwork for the maps of the first Spanish seismic codes PGS-1 (1968) and PDS-1 (1974).

At the beginning of the 1980s the probabilistic methods started to be used and were applied to seismic data of higher quality thanks to a breakthrough in networks and catalogues (Mezcua and Martínez Solares 1983; Vidal 1986). Different analyses were developed for a return period of 500 years using the Gumbel distribution (Martín and Sierra 1984; Roca et al. 1984) and results were obtained ranging from VII to X (MSK) for the largest part of the region, with a high dispersion. In general, maximum expected values appeared in Seville, Granada and Almería provinces. Muñoz (1983) and Muñoz et al. (1984) used a Poisson distribution of seismicity and a zoning method, getting maximum expected intensities around VII and VIII (500 year return period) for Almería and Granada. Martín (1983) also tested other seismicity models (Gumbel I distribution, zoneless method, different earthquake catalogues) and obtained different results depending on the method used, where Granada recorded larger intensity than Almería.

The representation of maps in terms of PGA started out in the 1990s, although the corresponding studies were carried out in terms of macroseismic intensity, eventually converted into PGA through equations derived from data of other parts of the world. As a consequence of the large dispersion inherent to Intensity-PGA relationships, hazard estimations varied largely from one author to another.

Molina (1998) used the standard zoning method and included two different attenuation models. He obtained mean PGA values for the 500-year return period ranging from 30 cm/s^2 in the northern boundary of the region to 80−110 cm/s^2 (depending on the model adopted) in parts of Malaga and Granada.

Cabañas et al. (1999a) and Calvert et al. (2000) carried out a study in terms of spectral accelerations and estimated the response spectra in the capitals of Andalusia, mentioning the influence of the Azores-Gibraltar seismicity in the cities of Western Andalusia, Seville, Huelva and Cádiz, where the spectra present a higher content of low frequencies. This circumstance had already been pointed out by Benito and López-Arroyo (1991).

Peláez (2000) and Peláez and López-Casado (2002) carried out a study combining zoning with zoneless methods and the results range between PGA values of 0.08 g in the northern boundary and 0.32 g in Granada and Seville. In a new study Peláez et al. (2003) included data of active faults the Granada basin obtaining PGA values multiplied by a factor 2 compared with the ones given by Peláez (2000) for Granada.

Crespo and Martí (2002) compared the estimations obtained by zoning and zoneless methods in some Spanish cities and found that the values were not very different; e.g. in Huelva PGA is 0.10 g with the first method and 0.12 g with the second method.

Jiménez and García-Fernández (1998) and Jiménez and García-Fernández (1999) obtained different PGA maps depending on the ground motion predicted parameter, the seismicity model and the attenuation relation adopted. Their results consistently showed that hazard increases from the northern part of Andalusia to the Granada Basin, although the predicted PGA values varried strongly depending on the input parameters selected.

Jiménez et al. (2001) developed the seismic hazard map in the frame of the it Global Seismic Hazard Assessment Program (GSHAP) and obtained PGA maps with values ranging from 0.08 (north of Andalusia) to 0.24 g (in the Granada basin). Finally, similar PGA values in hard soil for the region of Andalusia were given in the seismic hazard map of the last version of the Spanish Building Code (2002; hereafter referred to as NCSE-02).

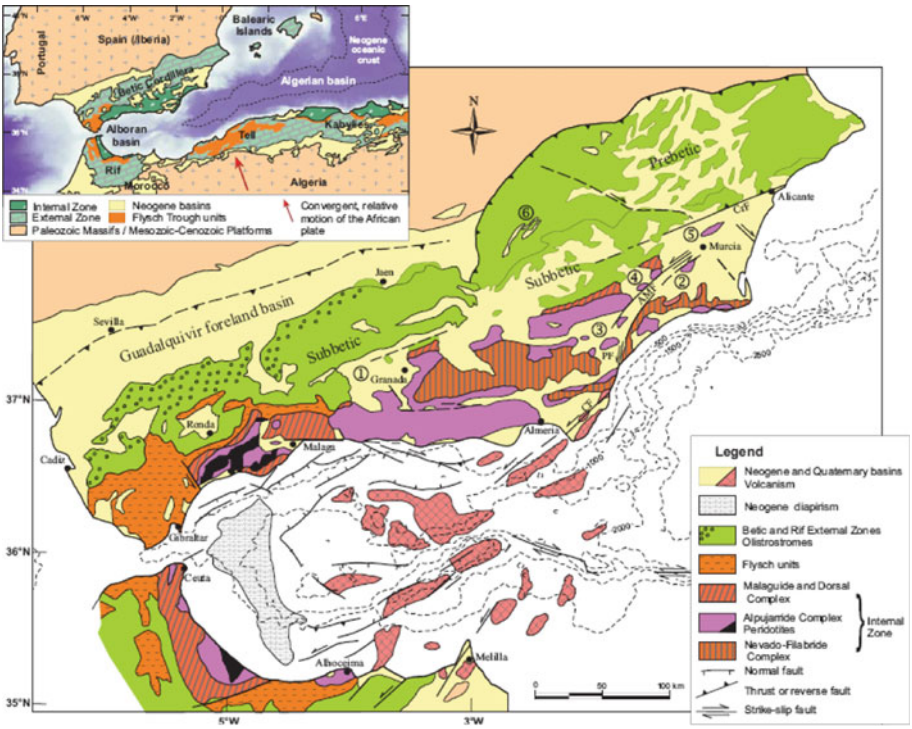

Fig. 1 Tectonic map of the Andalusian region (after Meijninger 2006)

3 Sismotectonic frame of Andalusia

3.1 Regional tectonic setting

The main geologic structures of Southern Spain include, besides the southern boundary of the Iberian Variscan massif, the Betics and the Guadalquivir Basin (Vera et al. 2004). Figure 1 shows the tectonic map of the region. The Betics range represents the northernmost part of the Alborán region, a tectonic domain located in the western part of the Alpine orogenic belt. This domain, consisting of the Alborán Sea and the Betics and Rif ranges, has experienced a complex Neogene deformation distributed over a broad zone (more than 500 km wide) stretching from the High Atlas in Morocco to the Betics in Spain (Calvert et al. 2000), an important reason to explain the recent diffuse seismicity and a non clear plate-boundary between Africa and Iberia.

The Betics is a fold-and-thrust belt typically divided into Internal and External zones owing to a pronounced difference in timing, style of deformation, and lithology. The Internal zone is composed by Precambrian, Paleozoic and Triassic metamorphic rocks (Nevado-Filábride and Alpujárride complexes) and by non-metamorphic Paleozoic, Mesozoic and Tertiary sediments (Maláguide complex) (Fontboté 1986).

The external zone comprises highly deformed (thrusted and folded) Mesozoic and Paleogene marine sediments deposited along the former Iberian continental paleomargin. It can also be divided into two units: the Prebetic is composed by shallow marine platform deposits

and the Subbetic by deep continental talus and pelagic sediments (García-Hernández et al. (1980)). An intermediate zone of highly deformed flysch, consisting of nappes of Early Cretaceous to early Miocene sediments, separates the Internal and External zones in the Western Betics (Fig. 1). The crustal thickness of mountain ranges may have been locally in excess of 50 km in the internal zone.

Active extension in the Betics continued until the end of the Miocene. In the Pliocene and Quaternary, gross plate motions reasserted control of the deformation in the region with primarily NNW-SSE shortening and strike-slip faulting (Calvert et al. 2000), which coexisted with radial extensional stress pattern in the (Western) Alborán Basin. During the rise of the Betics, several basins developed. The most important of them is the Guadalquivir Depression, the Neogene northern foreland basin of the Betics, widening southeastwards. Other small Neogene intramontane pull-apart basins are located within the Betics, accommodating strong internal deformation (Huércal-Overa, Guadix-Baza, Granada basins) and their development was determined by strike-slip faults.

3.2 Seismicity

Andalusia presents a moderate seismic activity associated with the continent-continent collision between Africa and Eurasia plates which is distributed over a wide area. Seismic energy is released predominantly through frequent, small seismic events (Grimison and Chen 1986) and unusually through earthquakes of moderate magnitude. Most earthquakes are generated at shallow depths ($h < 40$ km), a significant number at intermediate depth ($40 < h < 150$ km) and there are only a few very deep events (≈630 km) (Vidal 1986; Morales et al. 1997). The region is acknowledged to be the most seismically active zone in Spain according to historical and instrumental seismic data and it is considered the most hazardous seismic zone by the Spanish Building Code NCSE-02.

Regarding the instrumental seismicity, the Andalusian events were first detected with a few local stations at the beginning of the twentieth century, with a gradually improved national seismic network later on, mainly since 1962 and especially from 1983 to the present, with the deployment of two local seismic networks as well (Alguacil and Martín Dávila 2003). The mainland Andalusian earthquakes instrumentally recorded are generally of low magnitude ($M_w \leq 5.5$) with the exception of the 1910 Adra coast earthquake (M_w 6.2) and the very deep 1954 Dúrcal earthquake (M_w 7.9).

Nevertheless, several strong earthquakes ($M_w \geq 6.5$) have taken place in surrounding areas during the last half century: those of 1954, 1980 and 2004 in Northern Algeria, 2004 in Northern Morocco and 1969 and 2007 in the Gorringe Bank (SW Saint Vincent Cape, Portugal). The high magnitude of these events indicate the likely influence of their respective seismogenic zones in the seismic hazard of Andalusia.

The historical seismicity of Southern Spain is not well known for the period before the 16 th century, when the area was under Islamic rule. During that period most primary historical sources are lost and the discovery of documents is rare and fragmentary. After the 15th century the situation gradually improves. Historical documents show that most of the strongest earthquakes in Spain occurred in the Betics region (Southern and Southeastern Spain). From the fifteenth to the twentieth centuries several strong and damaging earthquakes took place with onshore epicentral location in this region, being the most important those of the years 1431, 1522, 1680, 1804, 1829 and 1884, with an intensity $I_{EMS} \geq$ IX; others occurred in 1406, 1504, 1518, 1531, 1644, 1658, 1674, and 1806 that reached an intensity $I_{EMS} \geq$ VIII. Other important historical shocks with epicentre in the sea but with high felt intensity inland, $I_{EMS} =$ VIII, are those of 1494 in the south of Málaga, 1357 and 1487 in the Gulf

of Almería, and 1722 and 1856 in the Gulf of Cádiz. Furthermore, a relative distant marine active zone located SW of Saint Vincent Cape (Portugal) is the source of large magnitude earthquakes such as those of 1356 and 1755 affecting Southwestern Spain. The most important one is the 1755 Lisbon earthquake, M_w magnitude around 8.5, felt with I_{EMS}= VIII in Huelva and Seville (Martínez Solares and López Arroyo 2004) with the highly destructive tsunami in the coast of the Gulf of Cádiz and Huelva, causing more than 1,200 casualties in the Spanish territory. All these seismic events have become crucial in seismic hazard studies of this region.

3.2.1 Review of historical seismicity

Due to moderate level of seismicity of Andalusia, the recurrence period of severe earthquakes is generally larger than hundreds of years in each seismogenetic zone. The reappraisal of the historical seismicity of Andalusia has been necessary because the instrumental records span over nearly one century, a period definitely insufficient to characterize the seismicity of the region.

In the present study, a deep review of the more relevant historical earthquakes ($I_{EMS} \geq$ VII or $M_w \geq 5.0$) that occurred from 1000 to 1904 AD in Andalusia and neighbouring zones was carried out using available historical documents. The seismic intensity values (EMS-98) of the affected towns, maximum intensity, epicentral coordinates, magnitudes and other earthquake parameters have been estimated as best as possible based on damage description and/or the spatial extents of felt area.

The historical seismicity had already been studied by many authors (Sánchez Navarro-Neumann 1917, 1921; Rey Pastor 1936; Alcocer and López Marinas 1983; Arenillas Parra et al. 1983; Rodríguez de la Torre 1990, 1993; Espinar 1994; Espinar et al. 1994; Olivera 1995; and Bretón 1997, among others). As a result different catalogues were compiled by Galbis (1932) and Galbis (1940); Mezcua (1982); Mezcua and Martínez Solares (1983), Instituto Andaluz de Geofísica (IAG, Vidal 1986, 1993) and Instituto Geográfico Nacional (IGN, Martínez Solares and Mezcua 2002).

The IGN earthquake catalogue was used as initial database for our study, taking into account the IAG catalogue. The first step was to inspect all the events belonging to Andalusia and surrounding areas (34.0°N – 41.0°N; 10.0°W – 3.0°E) with intensity $I_{EMS} \geq$VI or with magnitude $m_{bLg} > 5.0$, and check all of them in order to reappraise and find possible errors in earthquake parameters. As a result, 577 historical and instrumental earthquakes, including several dubious ones, underwent some modifications with respect to earlier studies. After considering all possible historical damaging events of the area, all of them were critically reviewed. A second deeper review of the most significant earthquakes ($M_w \geq 5.5$ or $I_{EMS} \geq$ VII) occurred in Andalusia and adjacent areas (35.0°N – 39.0°N; 8.0°W – 1.0°W) were carried out (Table 1), conducting a more detailed study in 73 of them because they were reported with abundant historical documentation.

Regarding the availability and quality of data, historical earthquake data can be classified according to the three historical time periods belonging to the 11–15th, 16–19th and 20th centuries, respectively. The first period is incomplete for events with intensity I_{EMS} lesser than IX since the historical record is scarce for this period. Nevertheless, we re-evaluated maximum epicentral intensity of eight events (see Table 1) and found a new important earthquake in April 24th, 1431 (I_{EMS} = VIII–IX) and the epicentres of all these events were macroseismically relocated. For the first and second periods, the maximum epicentral intensity of the largest events was reduced in many cases in one or a half degree in relation with the starting catalogue, and 16 of the 35 re-evaluated events with $I_{EMS} \geq$ VII changed

Table 1 Earthquakes of Andalusia and surrounding areas. 1000–2007 period with $M_w \geq 5.5$ or $I \geq VII_{EMS}$. Zone 35.0°N – 39.0°N; 8.0°W – 1.0°W

Date	Time	Latitude	Longitude	Depth	Intensity	Magnitude	Location
15/03/1024	00:00:00	37.90	−4.70		VIII-IX		Córdoba
01/01/1048	00:00:00	38.08	−0.92		VIII		Orihuela.A
01/01/1169	00:00:00	38.08	−4.17		VIII-IX		Andujar.J
01/03/1258	00:00:00	38.83	−0.60		VIII		Ontinyent.V
01/01/1344	00:00:00	38.90	−8.80		VII–VIII		Benavente.POR
24/08/1356	00:00:00	36.50	−10.00		VIII–IX		SW. Cabo San Vicente
14/05/1357	00:00:00	36.83	−2.33		VIII		Almería
18/12/1396	12:00:00	39.08	−0.22		VIII–IX		Tavernes de la Valldigna.
01/01/1406	00:00:00	37.15	−1.85		VIII		Mojácar. Al
24/04/1431	14:00:00	37.15	−3.63		VIII-IX		S. Granada
27/06/1431	00:00:00	37.25	−3.70		IX		S. Granada
01/11/1487	00:00:00	36.83	−2.47		VIII		Almería
26/01/1494	20:00:00	36.58	−4.42		VIII		S. Málaga
05/04/1504	09:00:00	37.47	−5.66		VIII-IX		Carmona. Se
09/11/1518	23:30:00	37.23	−1.87		VIII		Vera. Al
09/11/1518	23:40:00	37.23	−1.87		VIII-IX		Vera. Al
22/09/1522	10:00:00	36.83	−2.50		IX		SW de Almería
04/07/1526	23:00:00	37.18	−3.57		VII		Granada
30/09/1531	04:00:00	37.53	−2.75		VIII-IX		Baza. Gr
21/10/1578	04:00:00	35.27	−2.93		VIII		Melilla
18/06/1581	07:30:00	36.72	−4.42		VII		Málaga
31/12/1658	07:00:00	36.83	−2.30		VIII		Almería
05/08/1660	18:00:00	35.17	−2.92		VII		Melilla
28/08/1674	21:30:00	37.68	−1.70		VIII		Lorca. Mu
09/10/1680	07:00:00	36.85	−4.60		VIII–IX		W. de Málaga
27/12/1722	17:30:00	36.40	−7.77		VIII		Golfo de Cádiz
09/03/1743	16:00:00	38.00	−1.13		VII		Murcia
09/05/1750	00:00:00	37.20	−7.00		VII		Huelva
04/03/1751	00:00:00	37.65	−2.07		VII		Velez Rubio. Al
12/04/1773	05:15:00	36.00	−7.00		VII		Golfo de Cádiz
13/01/1804	17:53:00	36.50	−3.50		VII–VIII		Mar de Alborán
21/01/1804	04:53:00	36.50	−3.50		VII		Mar de Alborán
25/08/1804	18:30:00	36.80	−2.83		VII		Dalías. Al
25/08/1804	08:25:00	36.80	−2.83		VIII–IX		Dalías. Al
27/10/1806	12:30:00	37.23	−3.73		VIII		Pinos Puente. Gr
11/02/1848	01:30:00	35.30	−3.00		VII		Melilla
12/01/1856	11:20:00	36.75	−7.67		VII–VIII		Golfo de Cádiz
22/08/1862	17:00:00	37.05	−5.17		VII		Villanueva de San Juan. Se
25/12/1884	21:08:00	36.96	−3.98		IX–X		Arenas del Rey. Gr
05/01/1885	17:35:00	36.96	−3.98		VII		Arenas del Rey. Gr
27/02/1885	11:25:00	36.96	−3.98		VII		Arenas del Rey. Gr

Table 1 continued

Date	Time	Latitude	Longitude	Depth	Intensity	Magnitude	Location
11/06/1894	03:30:00	37.12	−2.67		VII		Nacimiento. Al
10/02/1901	00:00:00	36.75	−5.37		VII		Grazalema. Ca
25/05/1901	03:25:00	36.70	−3.50		VII		Motril. Gr
16/04/1907	17:30:00	37.80	−1.50		VII		Totana. Mu
29/09/1908	00:00:00	38.10	−1.30		VII		Ojos. Mu
21/01/1909	00:00:00	35.50	−5.60		IX		Romara. MAC
04/05/1909	18:57:00	38.60	−7.90		VII		Evora. POR
12/01/1910	19:37:00	38.40	−8.00		VII		Viana Do Alentejo. POR
16/06/1910	16:27:30	36.67	−2.92		VII		Adra. Al
16/06/1910	04:16:41	36.67	−2.92		VII	6.2	Adra. Al
11/09/1910	01:37:00	38.80	−7.80		VII		Estremoz. POR
21/03/1911	14:15:35	38.02	−1.22		VII–VIII	5.6	Las Torres De Cotillas. Mu
03/04/1911	11:11:11	38.10	−1.20		VII–VIII		Lorqui. Mu
10/05/1911	09:55:30	38.10	−1.20		VII		Lorqui. Mu
16/05/1911	22:20:21	38.10	−1.20		VII		Lorqui. Mu
31/05/1911	15:13:44	37.20	−3.70		VII	4.9	Santa Fe. Gr
04/06/1911	16:53:09	37.20	−3.70		VI–VII		Santa Fe. Gr
22/04/1912	03:22:45	37.03	−2.95		VII		Ocaña. Al
11/08/1913	01:05:48	36.80	−3.20		VII	4.8	Albuñol. Gr
25/11/1913	02:27:29	37.78	−2.53		VII		Huescar. Gr
28/01/1917	22:32:31	38.03	−1.27		VII		Las Torres De Cotillas. Mu
28/04/1918	10:11:00	37.22	−3.68		VII		Atarfe. Gr
27/07/1922	03:01:12	36.98	−3.57		VII		Durcal. Gr
28/02/1926	22:12:24	38.58	−7.90		VII		Evora. POR
09/07/1923	15:31:12	35.57	−3.52		VI	5.7	Mar De Alboran
11/10/1926	06:39:18	35.70	−2.78		VII	5.6	Mar De Alboran
17/11/1926	21:21:31	35.68	−3.37		VII	4.5	Mar De Alboran
05/07/1930	23:11:44	37.62	−4.63		VII	5.4	Montilla. Co
03/09/1930	09:59:58	38.07	−1.23		VII	3.7	Lorqui. Mu
05/03/1932	02:10:26	37.42	−2.45		VII	4.8	Lucar. Al
28/05/1936	00:28:47	36.70	−5.33		VII	4.6	Villaluenga Rosario. Ca
20/09/1938	13:31:24	35.00	−5.70		VII		Alcazarquivir. MAC
05/03/1940	01:50:25	36.87	−5.33		VII	5.0	El Gastor. Ca
23/02/1944	22:34:10	38.17	−1.15		VII	3.8	Fortuna. Mu
23/06/1948	03:43:55	38.14	−1.76		VII	5.2	Cehegin. Mu
10/03/1951	10:38:36	37.59	−3.97	14	VII	5.2	Linares. J
19/05/1951	15:54:19	37.58	−3.93	18	VII	5.3	Alcaudete. J
08/01/1954	16:33:50	36.93	−3.88		VII	4.2	Arenas Del Rey. Gr
29/03/1954	06:16:05	37.00	−3.60	657	V	7.9	Durcal. Gr
04/06/1955	03:41:35	37.13	−3.65	5	VII	5.1	Albolote. Gr
19/04/1956	18:38:54	37.19	−3.68	5	VII	5.0	Albolote. Gr
05/12/1960	21:21:47	35.69	−6.62	5	VII	5.2	Golfo de Cádiz

Table 1 continued

Date	Time	Latitude	Longitude	Depth	Intensity	Magnitude	Location
15/03/1964	22:30:26	36.13	−7.75	30	VII	6.2	Golfo de Cádiz
09/06/1964	02:33:35	37.74	−2.57	5	VII	4.8	Sw Galera. Gr
09/09/1964	09:39:45	37.09	−3.62	5	VII	4.7	Se Otura. Gr
07/04/1970	09:16:14	35.10	−3.82	5	VII	4.9	E Tamassint. MAC
16/03/1972	21:31:32	37.42	−2.24	5	VII	4.8	Nw Partaloa. Al
23/12/1993	14:22:35	36.78	−2.94	8	VII	5.0	S Berja. Al
04/01/1994	08:03:15	36.57	−2.82	2	VII	4.9	Alborán Norte
26/05/1994	08:26:53	35.22	−3.95	5	VIII	6.0	W Alhucemas. MAC
22/12/1999	17:36:57	35.23	−1.39	11	VII	4.4	W Ain Temouchent. ARG
10/12/2002	13:51:30	36.15	−7.55	56	II–III	5.6	Golfo de Cádiz
24/02/2004	02:31:19	35.15	−3.93	17		5.5	Ne Tamassint. MAC
24/02/2004	02:27:46	35.16	−3.98		VIII	6.2	N Tamassint. MAC
13/12/2004	14:16:12	36.27	−9.99	53	III	5.7	Sw Cabo De San Vicento

slightly their epicentres with respect to the starting catalogue. In several cases maximum old intensities reflected influence of local conditions or topographical effects and not the epicentral intensity I_0 (or I_{EMS} in our case). The last period has only a few light changes in magnitude, location or intensity for 18 seismic events. A summary of the earthquakes with maximum felt intensity in Andalusia $I_{EMS} \geq$ VII or $M_w \geq 5.5$ is shown in Table 1 and Fig. 2.

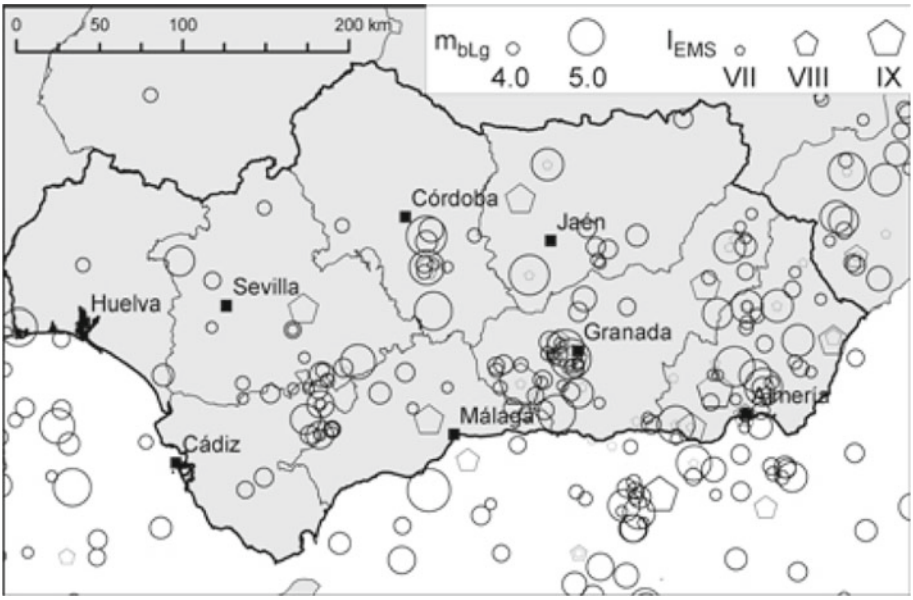

Fig. 2 Epicentre distribution of the historical (*diamonds*) and instrumental (*circles*) events in the Andalusian region and neighbouring areas, with M ≥ 5.5 or I ≥ *VII* (EMS). Zone 35.0°N − 39.0°N; 8.0°W − 1.0°W

4 Seismic hazard approach (rock sites)

The seismic hazard analysis followed a probabilistic zoning method framed in the well known PSHA (Probabilistic Seismic Hazard Assessment methodology (e. g., Budnitz et al. 1997)). A logic tree with two nodes for capturing epistemic uncertainty related to seismic zoning and ground-motion models was formulated. In a first phase, the inputs for the application of this method were prepared: seismic catalogue, seismogenics models and attenuation laws. Next the criteria followed to select and weight the different seismic zonings and ground-motion models that configure the branches of the logic tree were adopted.

4.1 Seismic catalogue

A seismic catalogue was created taking as initial database the information compiled in the catalogues of the Instituto Geográfico Nacional (IGN) and the Instituto Andaluz de Geofísica (IAG). The former is the official seismic catalogue of Spain. It includes a revised historical (prior 1900) catalogue for Spain (Martínez Solares and Mezcua 2002), where 1,686 earthquakes are documented with macroseismic intensity in the EMS-98 Scale. The latter is a catalogue of earthquakes with Moment magnitude M_w (IAG Regional Moment Tensor Project, Stich et al. 2003). Following the analysis of the above-mentioned historical earthquakes with $I_{EMS} \geq$ VII, a revised catalogue was built.

Thus a project catalogue for the influence area (considering an extension around 300 km from the boundary of the Andalusian territory) was obtained. The area was extended further westwards in order to include the Azores-Gibraltar seismogenic zone, whose seismicity may have a significant influence in the hazard. In a second step a depuration process was developed, by doing away with the fore and aftershocks, because we were assuming a Poisson model for the seismicity of every zone. The project catalogue was de-clustered using the following procedure. First, events catalogued as aftershocks in the IGN catalogue were removed. Then, the program Series-Buster (Álvarez-Gómez et al. 2005) was used to identify seismic series. Two events are considered to belong to the same seismic sequence if they occured within a time span of up to 10 days and a within a distance equal or lower than 10 km. A total of 955 series were detected and the corresponding after- and fore-shocks eliminated from the final project catalogue.

As the original catalogue includes data of magnitudes in different scales, including m_b, m_{bLg} and M_S, a homogenization process was carried out for obtaining moment magnitude as size parameter for all the events. This required the development of relationships among the different parameters, depending on the region. Hence, the correlations among magnitude scales were obtained for 5 zones: Iberian Peninsula, Cádiz Gulf, Azores-Gibraltar zone, Alborán Sea and Northern Africa. The data of M_w has been taken from the IAG catalogue M_w completed with other national or international agencies (IGN, ISC, NEIC, etc.).

The correlations between m_{bLg} and M_w respond to the expression:

$$M_w = \alpha_1 + \alpha_2 \cdot m_{bLg} + \alpha_3 \cdot {m_{bLg}}^2 \tag{1}$$

with the coefficients $\alpha_{1,}\alpha_{2,}\alpha_3$ given in Table 2.

For the conversion between Intensity I_o and Moment magnitude M_w, other correlations were developed according to the equation:

$$M_w = \beta_1 + \beta_2 \cdot I_0 + \beta_3 \cdot I_0^2 \tag{2}$$

with the coefficients $\beta_{1,}\beta_{2,}\beta_3$ given in Table 3.

Table 2 Coefficients of the relationships $m_{blg} - M_w$

Zone	α_1	α_2	α_3
Iberian Peninsula and Alboran Sea	3.8860	0.6014	0.1615
North Africa	1.5074	0.8066	0
Cadiz Gulf	0.1817	1.0004	0
Azores	1.3494	0.7782	0

Table 3 Coefficients of the relationships $I_o - M_w$

Zone	β_1	β_2	β_3
Iberian Peninsula and North Africa	3.6506	−0.1043	0.0445
Cadiz Gulf and Azores	3.2320	0.3365	0
Alboran Sea	−2.2259	0.4533	0

Table 4 Initial year of the completeness periods for continental, marine and African zones

M_w	Iberian Peninsula	N. África	Marine
3.5–3.9	1910	1950	1960
4.0–4.4	1850	1920	1940
4.5–4.9	1750	1920	1920
5.0–5.4	1700	1900	1880
5.5–5.9	1470	1880	1870
6.0–6.4	1300	1780	1800
6.5–6.9	1200	1675	1760
≥7.0	1000	1675	1700

Also, 22 great historical earthquakes with M_w magnitude obtained from intensity points distribution were considered.

In the case of an epicentre in the sea, the only available data was the felt intensity I_s somewhere in the coast, then the epicentral intensity I_{EMS} was estimated through the relations obtained by Molina (1998) who distinguishes a zone of very low attenuation for the Atlantic coast and other zone with low attenuation for the Mediterranean coast.

In the cases in which the only available data is m_b or M_S, the general relationships given by Scordilis (2006) from data all over the world were applied.

$$M_w = 0.67 \cdot M_S + 2.07 \quad \text{if} \quad M_S \leq 6.1 \tag{3}$$

$$M_w = 0.99 \cdot M_S + 0.08 \quad \text{if} \quad M_S > 6.1 \tag{4}$$

and

$$M_w = 0.85 \cdot m_b + 1.03 \quad 3.5 \leq m_b \leq 6.2, \tag{5}$$

Finally, the completeness of the catalogue was analyzed according to the Stepp (1973) method, and the reference year from which the catalogue may be considered complete for each magnitude interval was estimated (shown in Table 4). The analysis was carried out independently for the Spanish territory, offshore areas and north of Africa (Fig. 3).

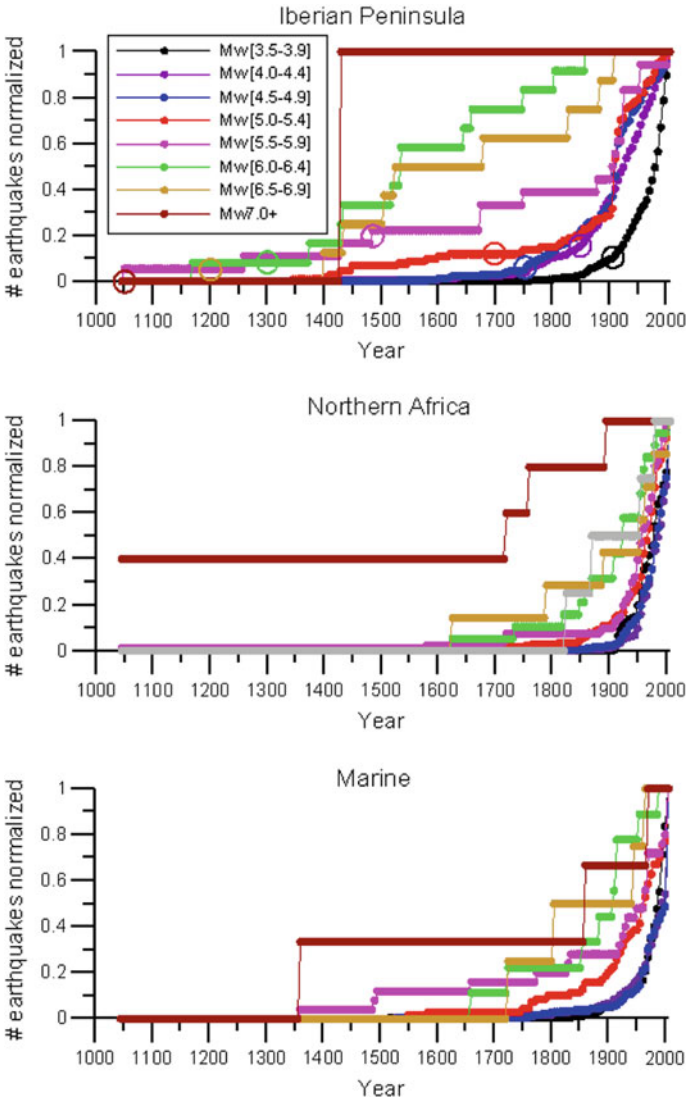

Fig. 3 Number of earthquakes catalogued per year. Each line represents different magnitude interval. Three different geographical regions are considered: Iberian Peninsula (*top*), North Africa (*middle*) and marine areas (*bottom*)

4.2 Selection of seismic zonings

Different zoning models were initially considered for the study region, including those of Martín (1983); Muñoz (1983); IPEEE (1993); López Casado et al. (1995); Molina (1998), the model defined for the Global Seismic Hazard Assessment Project (GSHAP), Bouhadad and Laouami (2002), the model in which the hazard map of the Spanish seismic Building Code is based (NCSE-02), Peláez et al. (2006); Hamdache (1998) and Aoudia et al. (2000).

After a careful revision of the proposed source zoning models for the study region, three different seismic zonings were considered: the one adopted in the Spanish Seismic Building

Code (NCSE-02), the model of López Casado et al. (1995) (LC95), and the model defined for the Global Seismic Hazard Assessment Project (GSHAP). Although they might not be the most recent ones, they are selected for some reason that makes them adequate for the present study. NCSE-02 is the model in which the official map of the Spanish seismic code is based on. LC95 is a regional model just for Andalusia, which incorporates the tectonics of the area at the same scale. GSHAP is certainly similar to NCSE-02 model, but it also includes areas form northern Africa in the same model.

In order to obtain a first estimation of the impact that long-distance sources may have on long period ($T \geq 1.0$ s) spectral accelerations, we have supplemented the models NCSE-02 and LC95 with other zoning models defined for Northern Africa. In the case of LC95, the Azores-Gibraltar zone was considered from NCSE-02 (zone 12).

The north of Africa Zoning models were chosen after a revision of the specialized literature, finally considering the zoning proposed Hamdache (1998) supplemented by data of Peláez et al. (2006) (HAM98) and the zoning proposed by Aoudia et al. (2000) (AOU00). Both models seem quite reliable, and they are the most complete and best explained for northern Africa on the basis of the information taken into account for the definition of boundaries and estimation of seismic parameters. Thus they were selected to complete the Spanish models in that zones.

Figure 4 shows the three selected zoning for the Iberian Peninsula, together with the two models for North Africa. The NCSE-02 model is made up of wide zones, which were defined based largely on epicentre distribution and main regional geological features on a peninsular scale. LC95 is made up of much smaller zones, which were defined based on relationships found by the authors between the distribution of epicentres and fracture systems of the Betics. Finally, GSHAP is a model combining zones used for the hazard maps of the building codes of different countries: Spain, Portugal, Morocco and Algeria. Consequently, it involves a heterogeneous definition of zones: the zones for Spain, Portugal and Morocco are extensive, while the zones of Tunisia are small, and the Algeria model includes zones and faults.

Then 5 branches were included in the zoning node of the logic tree with the following composite models (Fig. 5):

Model 1: LC95 + HAM98+ Z12
Model 2: LC95 + AOU00+ Z12
Model 3: NCSE-02 + HAM98
Model 4: NCSE-02+ AOU00
Model 5: GSHAP

4.3 Selection of ground motion models

The Spanish Strong Motion Network started operating in the 1980s (cf. Carreño et al. 1999). To date, few studies have been done to provide local strong ground-motion relationships using these data (e.g., Martín et al. 1996; Cabañas et al. 1999b; Tapia 2006). However, these studies are based on a very limited dataset. Only 8 inland events of magnitude between 4.5 and 5.1 have been recorded in southern Spain since 1989, hence they cannot be considered representative for deriving strong motion models. Therefore, it is necessary to select other attenuation equations from the literature, drawn from statistically significant datasets and comprising wider magnitude and distance ranges.

Two main criteria have been considered for selecting ground-motion models: (1) that they should be derived from extensive databases, and also widely used in European countries located in a similar seismotectonic context (the European-African plate boundary) and

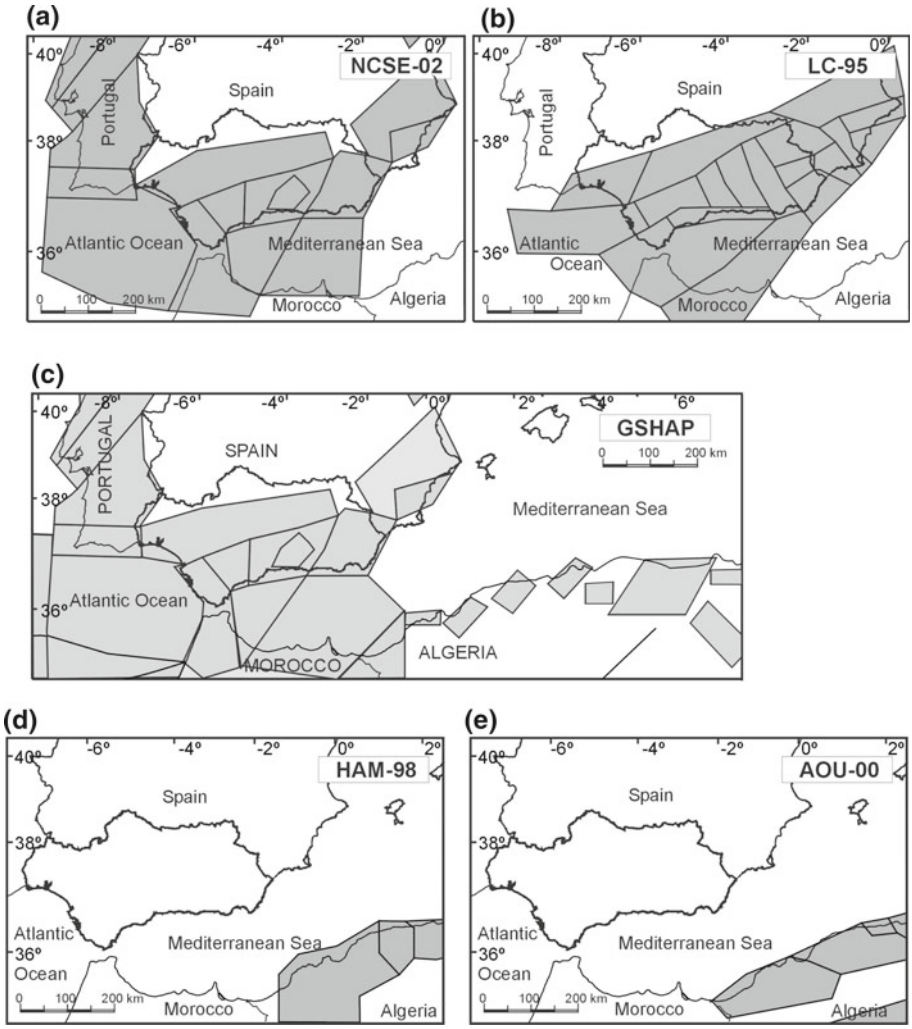

Fig. 4 Seismic zonings considered for the construction of the logic tree in the hazard analysis. **a**) NCSE-02 model; **b**) LC95 model (López Casado et al. 1995); **c**) GSHAP model. **d**) HAM98 (Hamdache 1998) **e**) AOU00 (Aoudia et al. 2000)

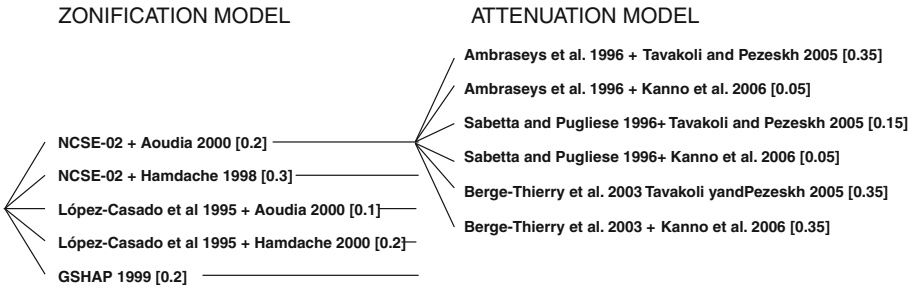

Fig. 5 Logic tree for hazard estimation. The weight assigned to each branch is pointed out in *brackets*

(2) that the independent variable should be given in terms of peak ground acceleration and spectral ordinates for a wide range of vibration periods (from 0.1 to 2.0 s). Considering the aforementioned criteria, we have finally selected the attenuation equations of Ambraseys et al. (1996) (AM-96), Sabetta and Pugliese (1996) (SP-96), and Berge-Thierry et al. (2003) (BT-03) for rock conditions.

On the other hand, it is well known that the ground motions with source in the Azores-Gibraltar zone have a different attenuation, which is slower than the ones in other directions. In fact, the earthquakes with epicentre in this zone, such as the 1755 or 1969 events, were felt in the whole Iberian Peninsula with a preferential northeastward propagation as reflected by the isosismal maps (Martínez Solares 2001). Existing attenuation laws in terms of macroseismic intensity (Martín 1983; Molina 1998) show that the attenuation is remarkably smaller for this region than the one corresponding to other parts of the region.

Data from the M_w 6.1 February 12th 2007 and the December 19th 1994 earthquakes, occurred in the Azores-Gibraltar zone and recorded by several strong-motion stations, were used in order to check other strong motion models and to choose the most suitable ones to simulate the attenuation of the motions with source in that zone.

In a first step, some models reflecting slow attenuation were chosen, namely the ones derived by Somerville et al. (2001); Campbell (2003, 2004); Tavakoli and Pezeshk (2005), and Atkinson and Boore (2006) for the stable zone of Eastern United States as well as other models proposed for subduction zones: Zhao et al. (2006) and Kanno et al. (2006) for Japan and Atkinson and Boore (2003) for Cascadia (NW coast of USA).

In spite of the high dispersion of the data, we can appreciate that the model of Tavakoli and Pezeshk (2005) (T&P05) fits in better with the recorded values of PGA and short period spectral accelerations. However, for long period accelerations the best fit is obtained with the model Kanno et al. (2006) (K06). Therefore, the models chosen for the Azores zones are T&P05 and K06 because they are the ones which fit in better with the data for both short and long periods.

The final models included in these hazard estimations are a combination of models for both the continental part and the Azores–Gibraltar zone, considering the next options:

Model 1: AM-96 + T&P05
Model 2: AM-96 + K-06
Model 3: SP-96 + T&P05
Model 4: SP-96 + K-06
Model 5: BT-03 + T&P05
Model 6: BT-03 + K-06

4.4 Formulation of the Logic Tree

We set up a logic tree consisting of two nodes: seismic source zoning and ground-motion attenuation model (Fig. 5). The former node splits into five branches that stand for the five zoning models presented in a previous section. The scheme of weights follows the general criteria: models with more reliable seismic and tectonic information are considered with a higher weight.

A doubly-truncated Gutenberg-Richter model for magnitude distribution was used to represent recurrence parameters of seismic zones. The threshold magnitude was set to $M_w = 4.0$ and the maximum expected magnitude M_{max} was 0.5 units higher than the maximum reported magnitude for each zone. For North African sources, where the review of the catalogue was

limited, maximum magnitudes were adopted from Hamdache (1998) and Peláez et al. (2006). A least-squares approach was used to derive the values of the Gutenberg-Richter curve, in which the number of earthquakes exceeding a certain magnitude value were estimated by extrapolating the constant recurrence rates obtained within the completeness period to the entire period of study.

Regarding the attenuation models, two basic factors are considered for the assignment of weights: the number of records used in each of the models and the applicability ranges, focusing on the magnitude and distance intervals that are statistically significant in the models. The frequent occurrence of low-magnitude, damaging earthquakes in Southeastern Spain compelled us to pay special attention to the lower bound magnitude from which the equations are statistically reliable. Regarding the distance range, we favored equations suitable for distances as long as possible.

A critical issue over the use of ground motion models in a logic tree is to achieve compatibility among different definitions of the dependent and independent variables (magnitude scales, type of source-to-site distance, measurement of the predicted parameter, Bommer et al. 2005). In this work, the surface wave magnitude (M_S) used in the attenuation models of AM-96 and BT-03 was converted to M_w using the equations of Scordilis (2006). Furthermore a compatibility between fault-distance and epicentral-distance was assumed which is reasonable for regional hazard calculations in areas where the frequency of large earthquakes ($M_w > 6.0$) is very low. Predicted parameter measurements were corrected using Beyer and Bommer (2006) approach. In this regard, the extrapolation of the models far from their applicability ranges (specially for lower magnitudes) should be avoided (Bommer 2007)

4.5 Estimation of seismic hazard: specifications and results

Seismic hazard calculations were carried out using the CRISIS code (Ordaz et al. 2001). The EXPEL tool (Benito et al. (2004); Consejo de Seguridad Nuclear (CSN, 2008)) was used to visualize and manage the different 30 solutions stemming from the logic tree.

A set of hazard maps was developed from a $0.1° \times 0.1°$ grid in terms of PGA and SA (T) for $T = 0.1, 0.2, 0.3, 0.5, 1$ and 2 s. As an example Fig. 6 shows the hazard maps of PGA, SA (0.2 s) and SA (1 s), representing in each case the weighted-mean acceleration values for the 475-year return period. This return period is the hazard level usually considered in seismic design of conventional buildings (e.g., Eurocode 8, NCSE-02), and it has also been the one considered in the SISMOSAN project.

The dispersion of the logic tree results is shown through the Coefficient of Variation (COV), defined as the ratio between the standard deviation and the mean value of the estimates given by the different branches of the logic tree. COV constitutes a measurement of the uncertainty related to the adopted nodes: zoning and strong motion models. The COV maps are shown in Fig. 7, giving an idea of the areas subjected to higher or lower variability to the alternative options represented in the logic tree (higher and lower COV values, respectively). Areas presenting a higher COV are subjected to higher epistemic uncertainty, and therefore, efforts to reduce it should be concentrated therein in the future.

As we can see in Fig. 6, the higher values of PGA (more than 200 cm/s^2) are expected in the Granada basin. In other parts of the Granada province, as well as in Almería and Eastern Málaga, the PGA values range between 120 and 160 cm/s^2. The value of this parameter decreases from the Betics towards the Guadalquivir Valley, where the values nearly reach 25 cm/s^2. Similar patterns are observed for the other spectral ordinates obviously changing amplitude. COV values range from 0.1 to 0.35 approximately. For PGA and SA (0.2 s) maps,

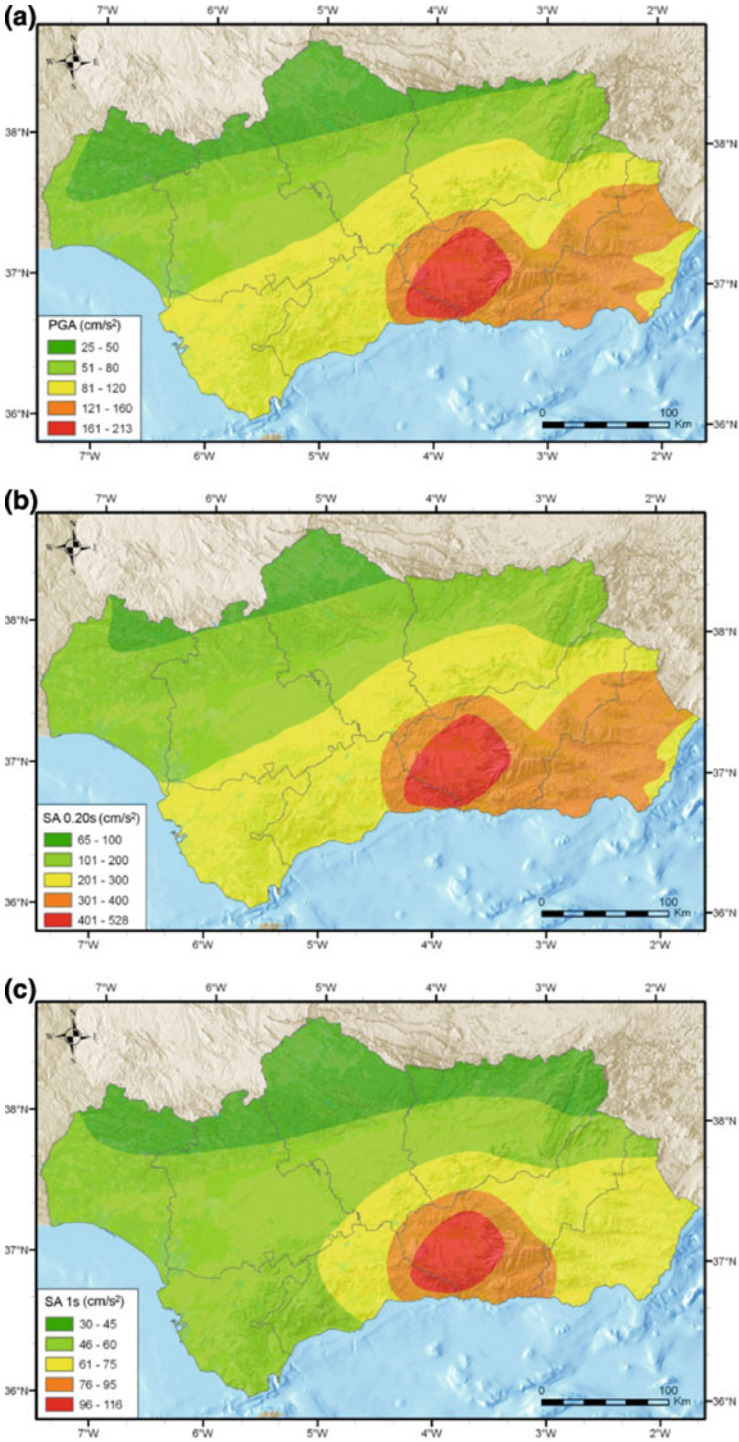

Fig. 6 Seismic hazard maps for a return period of 475 years. **a**) PGA, **b**) SA (0.2 s), **c**) SA (1 s.)

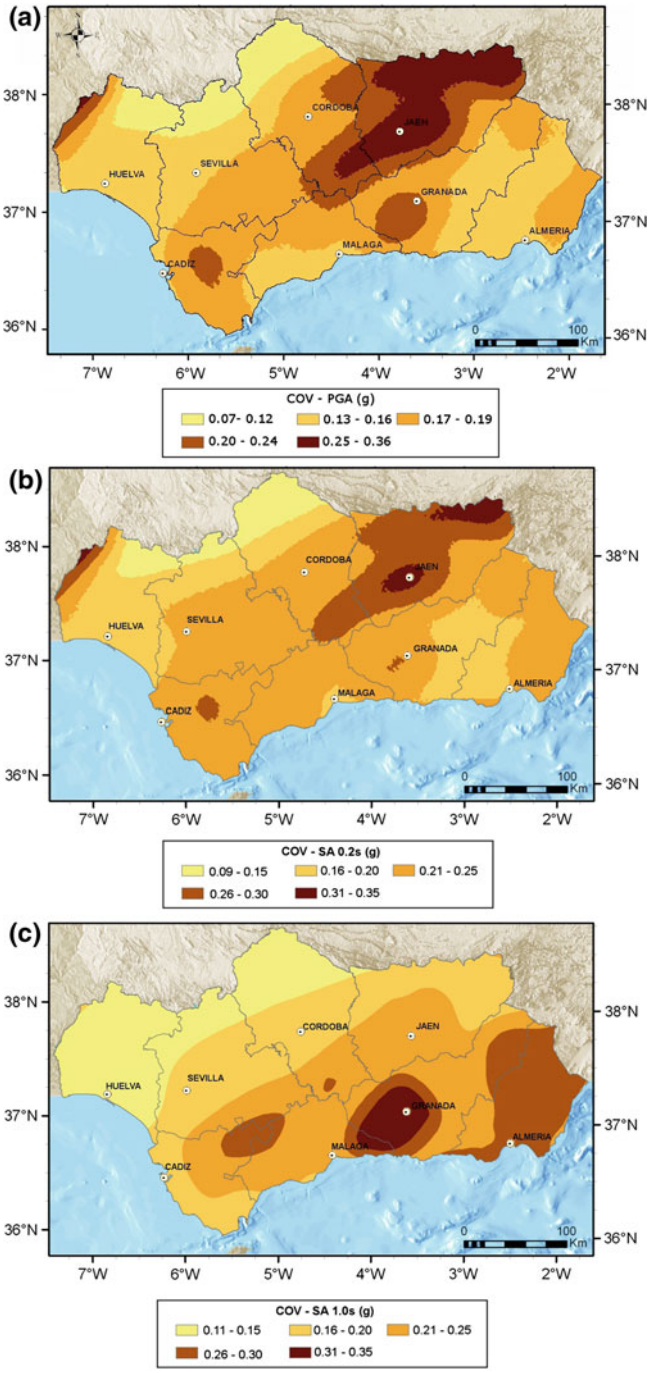

Fig. 7 Coefficient variation maps (COV) **a**) PGA, **b**) SA (0.2 s), **c**) SA (1 s.)

the largest COV values are found in the northeastern part of the region and for SA (1 s) around the Granada Basin.

5 Geotechnical classification and amplification factors

Seismic waves are gradually attenuated with propagation distance in the crust but amplified by the structures above the seismic bedrock (with $V_S \geq 3$ km/s), and especially by those surface soil layers located on the engineering bedrock (with $V_S \geq 0.75$ km/s). Local soil conditions have a relevant influence on the characteristics of seismic ground motion. The softness and thickness of surface soils are two important local geological factors affecting the level of earthquake shaking and their local variations can lead to spatial seismic intensity differences even in the cases of moderate earthquakes. Amplification of ground motion refers to the increase in the intensity of ground shaking that can occur due to local geological conditions, such as the presence of soft soils.

It is well known that earthquake damage is generally larger over soft sediments than on firm bedrock outcrops due to differences in the amplitude of ground motion. Several studies on Andalusian historical earthquakes (López Arroyo et al. 1980; Vidal 1986; Espinar et al. 1994; Vidal et al. 2006) concluded that severity and distribution of earthquake damage were associated to local soil conditions.

In order to estimate the amplification of seismic motion by surface soil layers, a regional and local geological division of the surface materials has been carried out taking into account both their geological and geotechnical characteristics and the nature of the substrate.

The Andalusian region shows a great geological complexity, which leads to a variety of lithologies of different origins and characteristics with a very heterogeneous distribution. Metamorphic, sedimentary and volcanic rocks with different development and age appear on the surface, as well as recent sedimentary soils belonging to Neogene-Quaternary basins, where most of the towns in the region are located. Some of these basins have thick sedimentary deposits, reaching up to a thickness of 3 km in the case of the Granada basin.

The spaciousness and geological complexity of the study area, coupled with the existence of lateral and depth ground heterogeneities, make difficult "in situ" acquisition of specific geotechnical parameters through field surveys and laboratory analyses for each emplacement. Consequently, a regional seismic-geotechnical classification of near-surface materials was performed, and afterwards an empirical correlation was made between each type of shallow structure and its average shear-wave velocity, thereby estimating the corresponding seismic amplification of each type of soil. The amplification factors have been assigned to each class based on averaging the shear wave velocity over a standard depth of 30 m (V_S^{30}) (Borcherdt and Glassmoyer 1992; Borcherdt 1994). This methodology has been internationally adopted since the 1994 NEHRP classification and it is appropriate to develop a regional probabilistic seismic hazard analysis (PSHA) improved by accounting for site effects.

The geotechnical classification starts by grouping the outcropping geological materials as presented in the Vectorial Digital Geological Maps of Andalusia at 1:50,000 scale (which defines 320 lithological units) and the more detailed Geological and Geotechnical maps of Andalusian relevant urban areas (with more than 20,000 inhabitants). The 132 lithologic groups established in the Geological and Mining map, 1:400,000 scale were used as reference. A new grouping of soils in 32 classes was made later mainly through geological (lithology, genesis and age) and seismic-geotechnical criteria (hardness/compactness, shear wave velocity, tectonization, saturation, neotectonics and thickness) as well as considering the results of recent research conducted in Andalusian

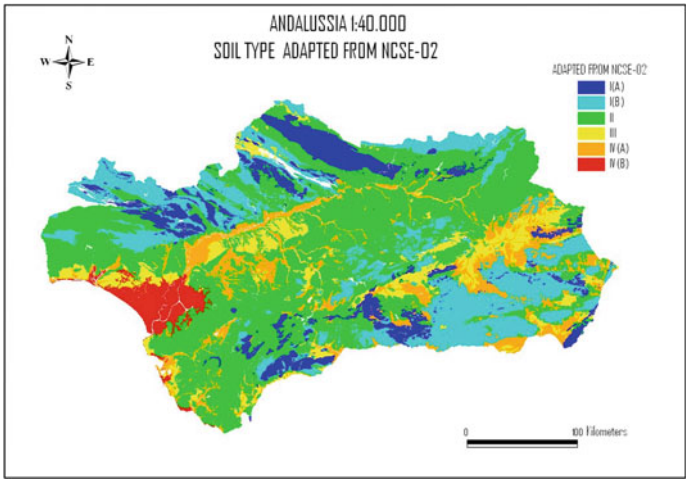

Fig. 8 Soil map according the adopted classification

urban areas (e.g. Navarro et al. 2001, 2007; Alcalá-García et al. 2002; Al Yuncha et al. 2004; García-Jerez et al. 2006). Then, those groups were classified considering their dynamic behaviour according to the average shear-wave velocity in the upper 30 m of soil, V_S^{30}.

In order to assign the V_S^{30} value to each material group, the values proposed empirically by different authors have been taken into account (Borcherdt 1994; Navarro et al. 2001, 2008; Benito et al. 2008; García-Jerez et al. 2008). According to the assigned V_S^{30} values, the geological sites were reduced to six reference site conditions on the basis of averaged shear waves velocity, namely: Soil type I is hard rock, Soil type II corresponds to rock, Soil type III is soft rock and very stiff soil, Soil types IV and V correspond to stiff soil and soft soil respectively, and Soil type VI to very soft soils (Table 5). This classification has similarities with that adopted in the 2003 NEHRP Provisions, (Building Seismic Safety Council 2004, herefore BSSC (2004). Regarding the four soil types proposed by the Spanish Building Code (NCSE-02), the current classification breaks up the first and the last soil classes of NCSE-02 in two new ground categories, resulting a total of six classes.

After seismic-geotechnical classification into six categories, seismic amplification factors were established for each class of soil mainly from V_S^{30}, following methods originally proposed by Borcherdt (1994) and after a comparative analysis with those contained in several regulations like BSSC-2004, Eurocode-98 and NCSE-02. The final site coefficients used in this study are shown in Table 5 for PGA and SA(T) of 0.1, 0.2, 0.5 and 1.0 s. The distribution of soil types is also shown in a zoning map (Fig. 8) that evidences the different dynamic behaviour from surface geological formations on the territory of Andalusia.

6 Expected ground motion including local effects

Seismic hazard for the 475-year return period including local effects has been estimated by the integration of results from previous phases, using a Geographic Information System (ArcInfo v.9.1). Seismic hazard maps at rock sites (Fig. 6) have been superposed on the soil classification map (Fig. 8) and the amplification factors (Table 5) have been applied over the values in rock sites. Figure 9 shows the results for PGA, SA (0.2 s) and SA (1 s). Clear differences can be

Table 5 Seismic-geotechnical classification of soils and amplification factors in the Andalusian region

Soil type	Geological description	Geothecnical description	V_S^{30} (m/s)	PGA	SA(T)			
					0.1 s	0.2 s	0.5 s	1.0 s
I	Igneous rocks: granites, Gabbra, basalts, andesites, etc. Metamorphic rocks: quartzite, marble, gneiss, etc. Sedimentary rocks: limestone and dolomites (Proterozoic, Paleozoic, Mesozoic)	High and very high hardness rocks slightly fractured	>1,500	0.87	0.84	0.80	0.80	0.80
II	Sedimentary rocks: dolomites, limestone and greywacke. Metamorphic rocks: schist, micaesquists and slate. (Paleozoic and Mesozoic)	Fractured rocks with high and very high hardness.	1,500–750	1.00	1.00	1.00	1.00	1.00
III	Metamorphic rocks: filites and metapelites (Paleozoic) Sedimentary rocks: sandstone, clay, limestone, marl, etc. Triassic rocks of Keuper: clay, gypsum, sandstone and limestone (Mesozoic, Cenozoic)	Medium-hard rocks highly fractured and sometimes with abundant intercalation of little toughness rocks Soft rocks with expansive clay.	750–400	1.20	1.20	1.20	1.39	1.70
IV	Quaternary sediments from river source, colluvial and foot of mount: sand, silt, conglomerates. (Tertiary and Quaternary)	Little or no cohesive soils promptly cemented.	400–200	1.40	1.50	1.60	1.90	2.40
V	Quaternary sediments from river, coluvial and wind origin: gravel, sand, silt and clay. (Quaternary)	Cohesive soft and loose not cohesive soils.	200–150	1.80	2.15	2.50	2.88	3.50
VI	Beach deposit, wetlands and river channels: mud, sand dunes, plastic clay and silt organic. (Quaternary)	Very soft soils, sometimes potentially liquefiable soils, sensitive clays, organic soils, soft clays, . . .	< 150	2.0	2.25	2.5	2.88	3.50

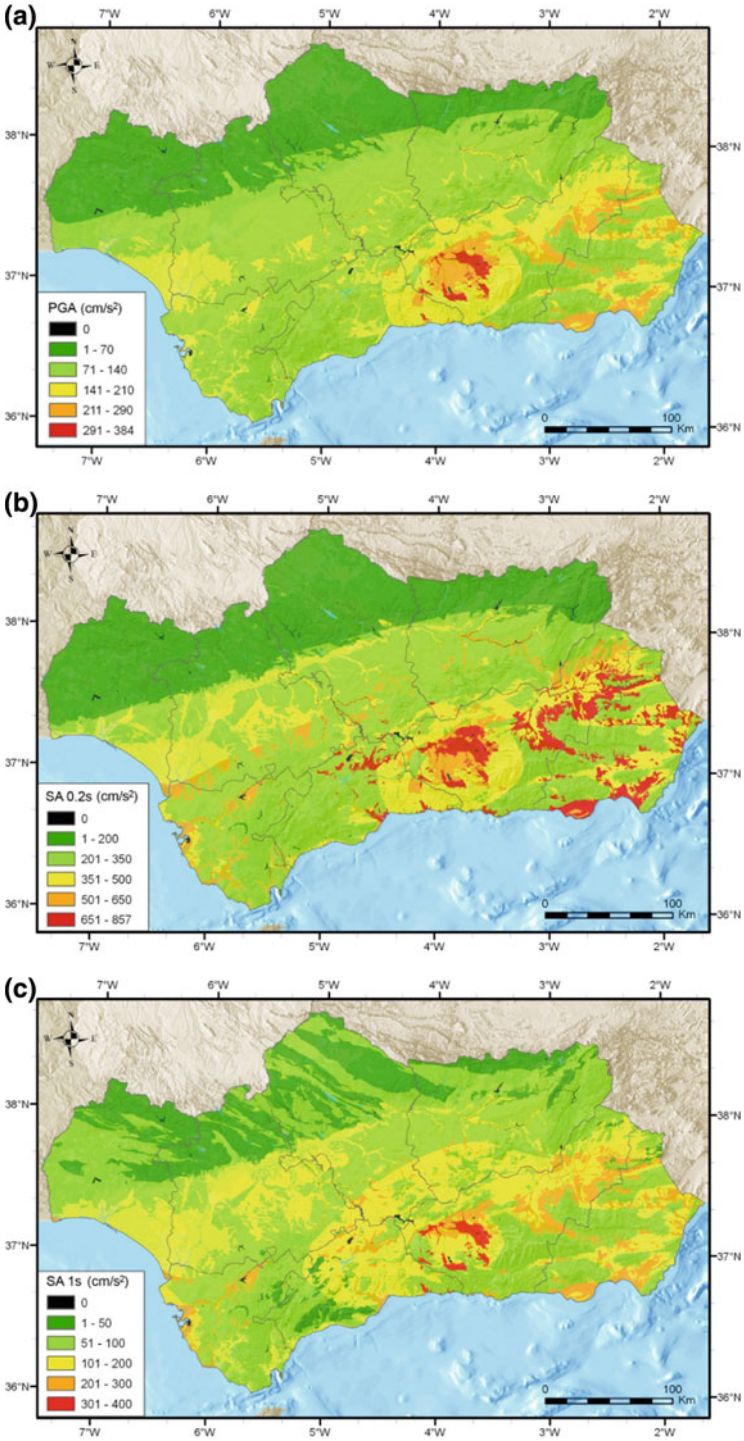

Fig. 9 Seismic hazard maps including local effect. **a**) PGA, **b**) SA (0.2 s), **c**) SA (1 s.)

observed between these maps and the previous ones in rock, as a result of the strong influence of soil conditions on the expected ground motion. In contrast to the smooth ground-motion gradients characterizing rock hazard maps, hazard maps including soil effects display short-wavelength spatial variations reflecting the great lithologic diversity of the region. Whereas areas with highest hazard are found in Neogene sedimentary basins, the lowest expected hazard is found in the Paleozoic Massif of the northern boundary of the region.

The new maps present an interval of PGA values between 24 and 396 cm/s^2 for the entire region. Maximun PGA values (>300 cm/s^2) are reached now in Granada province and the municipality of Vélez Málaga. The lowest values of PGA (<70 cm/s^2) occur in the northern part of the region. The highest expected spectral accelerations correspond to low periods (0.1 – 0.2 s) and reach a maximum from 651 to 857 cm/s^2 in Granada, Almería and Málaga provinces.

7 Conclusions

A new and complete seismic hazard analysis for Andalusia is presented in this paper, being the first study for the entire region developed in terms of peak ground acceleration and spectral ordinates.

As a starting point, a catalogue of the project was created after a careful review of the earthquakes with intensity $I_{EMS} \geq$ VII or magnitude $M_w \geq 5.5$. As a result, 16 out of 35 Andalusian historical earthquakes and 18 out 29 instrumental events were re-evaluated, changing intensity, location or (more rarely) magnitude parameters. I_{EMS} changes in historical earthquakes were a half or one degree smaller than previous ones in several cases and locations changed slightly with respect to the starting catalogues.

Due to the heterogeneity of the earthquake size parameters in previous catalogues, different relationships were used to convert all of them to moment magnitude M_w, obtaining in such a way a homogeneous catalogue more appropriate for seismic hazard applications.

The study has followed the PSHA methodology, with a logic tree consisting of two nodes associated to seismic source zoning and ground-motion attenuation model. Thus, the epistemic uncertainty inherent to these models has been quantified through the Coefficient of Variation COV. The greatest values of COV are found in the north central part of Andalusia due mainly to large differences among different proposals of seismogenetic zones.

Seismic hazard maps in generic rock sites obtained for a return period of 475 years show PGA values over 100 cm/s^2 in the largest part of Andalusia, reaching 140 cm/s^2 in parts of Granada, Almería and Málaga provinces, and the highest ones above 200 cm/s^2 in the Granada Basin. PGA decreases from the Internal Betics zone toward the Guadalquivir Valley and Sierra Morena, where PGA descends to 25 cm/s^2. Similar patterns of variation appear in the spectral acceleration maps (for 0.2 and 1 s). These results are quite similar to those presented in the NCSE02 Spanish Seismic Code.

The seismic-geotechnical classification in six categories and seismic amplification factors for each class of soil by using mainly V_S^{30} values proposed here, allowed quantifying the influence of soil conditions in the ground motion at a regional scale of this study. These categories have been established in such a way that an easy comparison with NCSE-02, Eurocode-08, BSCC-2004 and other seismic codes should be possible.

The new hazard maps estimated including site effects provide a more updated picture of the seismic hazard for the entire region than the previous ones, showing large horizontal gradients related to soil amplification contrasts. PGA values are in the range of 24–370 cm/s^2 for the whole Andalusian territory, with highest expected values (PGA > 300 cm/s^2) con-

centrated in the Granada province. Lowest values (PGA < 50 cm/s^2) correspond to some municipalities of Huelva and Córdoba. Similar trends are appreciated in SA value distribution although for the long period (1 and 2 s).

PGA and SA hazard maps including site effects clearly display short-wavelength spatial variations reflecting the great lithological diversity of the region.

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