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SEISMIC HAZARD IN ANDALUSIA REGION (SOUTHERN SPAIN).

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Abstract

The global objective of the SISMOSAN Project has been to provide a general seismic risk assessment of Andalusian region (Southern Spain) associated with the ground motions expected for a return period of 475 years. The project was financed by Civil Defence of Andalusia and its results will be applied to the definition of regional emergency plans. We present here the study and main results of the first phase of the project, aimed at evaluating seismic hazard. In contrast to most of the previous studies in the region, which were performed for peak ground accelerations (PGA) making use of Intensity-to-PGA relationships, hazard was here calculated in terms of magnitude and using published spectral ground-motion models. Moreover, we have considered distinct models for the Atlantic earthquakes, since the attenuation of those motions seem to be slower, as evidenced by the extensive macroseismic areas of the 1755, 1969 and 2007 earthquakes. A comprehensive revision of the seismic catalogue, as well as of the seismogenic models proposed for the region (including those for North Africa, which is part of the influence area) has been done. In a first step, seismic hazard was evaluated at generic rock sites covering the entire region, using a seismic catalogue homogenized to moment magnitude and considering attenuation models in terms of PGA and spectral ordinates (SA). A Probabilistic Seismic Hazard Assessment (PSHA) methodology was followed using a logic tree, in order to constrain the epistemic uncertainty, including two nodes for different options of zonification and attenuation models. In a second step, a geotechnical characterization of the whole region has been carried out, mainly inferred from geological maps and refined with on-site data, which are combined with rock acceleration estimates, in order to compose hazard maps that incorporate local soil effects.

Key-words: Historical earthquakes, reappraisal of earthquake parameters, earthquake catalogue, seismic hazard.

1. INTRODUCTION

Andalusia, located in southern Spain, is an area of low-to-moderate seismic activity in a global context, but one of the Spanish regions with higher seismicity. Damaging earthquakes have struck the region several times in the last 500 years; the I_{EMS} IX-X, December 25th, 1884 Arenas del Rey and the I_{EMS} IX September 22nd, 1522 Gulf of

Almería have been the more destructive events. In the last 20 years some earthquakes with magnitude Mw ~5 took place, causing some damage and big alarm in the population, like the December 12th, 1989 Ayamonte; December 23rd, 1993 Berja; January 4th, 1994 Adra and February 4th, 2002 Gergal earthquakes. Consequently, local authorities have promoted a seismic risk assessment study of Andalusia aimed at definition of the emergency plans, which has been named the SISMOSAN project. The first part of the project is the seismic hazard analysis presented in this paper.

This paper presents a new probabilistic seismic hazard assessment (PSHA) of the Andalusian region, accounting for the epistemic uncertainty in seismic source definition, and ground-motion attenuation, by means of a logic tree. The main results are hazard maps in terms of both PGA and SA. It is worthy to note two important peculiarities of the study. First, we have 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. Secondly, we follow a regional approach for including local effect in the seismic hazard estimations. As results of the study we develop, in a first phase, the hazard maps for rock conditions and for the 475-year return period in a wide range of spectral ordinates, and in a second step the hazard maps considering soil conditions. This is the first time that seismic expected ground motions, expressed as PGA, SA(T), and intensity (EMS) have been obtained for Andalusia including the influence of shallow ground structure on the shaking strength. These last maps show in a more realistic way the actual seismic hazard of the entire region.

2. SISMOTECTONIC FRAME

2.1. 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 represent the northernmost part of the Alboran region, a tectonic domain located in the western part of the Alpine orogenic belt. This domain, consisting of the Alboran sea and the Betics and Rif ranges, has experienced a complex Neogene continental 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). Active extension of 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 coexists with radial extensional stress pattern in the (western) Alboran Basin. During the building up of the Betics several basins developed. The largest one is the Guadalquivir Depression, the Neogene northern foreland basin of the Betics, widening southeastwards. Other smaller Neogene intramontane pull-apart basins are located within the Betics, accommodating strong internal deformation (Huércal-Overa, Guadix-Baza, Granada basins).

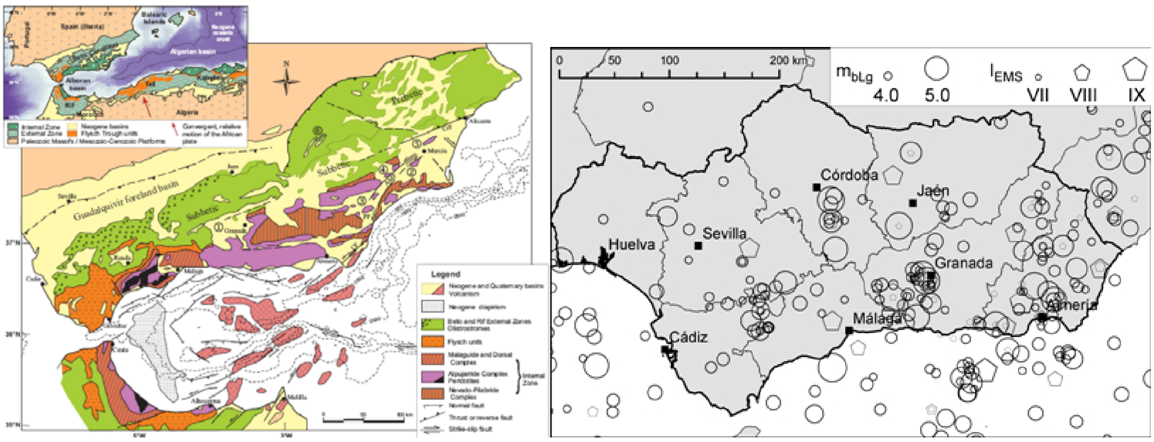


Figure 1. Left: geological map of southeastern Spain. Right. Epicenter distribution of the historical (pentagons) and instrumental (circles) events in Andalusia.

2.2. Seismicity

Andalusia presents a low-to-moderate seismic activity associated with the continent-continent collision between Africa and Eurasia plates and distributed over a wide area. Seismic energy is released predominantly through frequent, small seismic events (Grimison and Chen, 1986) and unusual earthquakes of moderate magnitude, most of them at shallow depth (h < 40 km), a significant number with foci at intermediate depth (40 < h < 150 km) and only a few rare very deep events (around 630km) (Vidal, 1986).

Regarding the instrumental seismicity, the Andalusian events were firstly detected with a few local stations at the beginning of the XX century, afterwards with a gradually improved national seismic network, mainly since 1962 and specially from 1983 to the present with the deployment of two local seismic networks also. The mainland Andalusian earthquakes instrumentally recorded generally are of low magnitude (Mw ≤ 5.5), exception done of 1910 Adra coast earthquake (Mw 6.2) and the very deep 1954 Durcal earthquake (Mw 7.0). Nevertheless, several strong earthquakes (Mw ≥ 6.5) occurred near Andalusia during the last half century: those of 1954, 1980 and 2004 in northern Algeria, 2004 in northern Morocco and 1969 and 2007 at the Gorringe Bank (SW Portugal); all them evidencing the influence of that seismogenetic zones in the hazard of Andalusia.

The historical seismicity of Southern Spain is not well documentary known for the period before 15th century, when the area was under the Islamic dominion. During XV to XX centuries, several strong and damaging earthquakes took place with onshore epicentral location, being the most important those of the years 1431, 1522, 1680, 1804, 1829 and 1884 with an intensity I_{EMS} ≥ IX and others occurred in 1504, 1518, 1522, 1531, 1645, 1658, 1674, 1748, 1806 that reached an intensity I_{EMS} ≥ VIII. Other important historical shocks, with offshore epicenter but with high felt intensity in land (I_{EMS} around VIII), are those of 1494 in South of Malaga, 1357 in Almeria Gulf, and 1856 and 1722 in the Gulf of Cadiz. Furthermore, a relative distant marine active zone located SW of Saint Vicent Cape (Portugal) is the source of large magnitude earthquakes as those of 1356 and 1755 affecting southwestern Spain. The most important one is the 1755 Lisbon earthquake, Mw magnitude around 8.5, and felt in Huelva and Cádiz with I_{EMS} VIII (Martínez-Solares, 2001). The related tsunami caused destructive effects in the Spanish coast of the Gulf of Cadiz, causing more than 900 casualties. All these seismic events are crucial in seismic hazard studies of this region.

In the present study, a review of the more relevant historical earthquakes (I≥ VII or M ≥5.0) that occurred from 1000 to 1904 A.D. in Andalusia was carried out using available historical documents and archaeological data. As a result, 68 historic earthquakes underwent some modifications with respect to earlier studies.

3. SEISMIC HAZARD ASSESSMENT

The seismic hazard analysis will follow a probabilistic zoning method framed in the well known PSHA methodology. A logic tree with two nodes for capturing epistemic uncertainty related to seismic zoning and ground-motion models are formulated. In a first phase, the inputs for the application of this method have been prepared: Seismic catalogue, seismogenic models and attenuation laws.

3.1. Seismic Catalogue

A seismic catalogue has been created, taking as initial data base the information compiled in the catalogues of the Instituto Geográfico Nacional (IGN) and the Instituto Andaluz de Geofísica (IAG). A deep revision of the historical earthquakes with I≥VII has been done (Vidal et al, 2009). After of this revision, a process of depuration and homogenization of the catalogue to moment magnitude has been carried out.

We prepared a final catalogue for the influence area, which is considered as the region in an extension of approximately 300 km from the boundary of the Andalusian territory. The area has been extended further to the west in order to include the Azores-Gibraltar zone, which seismicity has a significant influence in the hazard. All earthquakes in the defined area have been included in a first phase. In a second step a depuration process has been developed, taking away the fore- and aftershocks because we will assume later a poissonian model for the seismicity of every zone. As the original catalogue includes data of magnitudes in different scales M_b, M_{bLg}, M_S, etc, we have carried out a homogenization process for obtaining moment magnitude M_w as size parameter for all the events, described by Vidal et al (2009).. Finally, the completeness of the catalogue has been analyzed according the Stepp (1973) method and, taking the earthquakes in magnitude intervals of 0.5 and estimating the reference year for each interval, from which we can consider that the catalogue is complete in this interval. The analysis is done independently for the Spanish territory and North of Africa.

3.2. Selection of zonings and ground motion models: Logic tree.

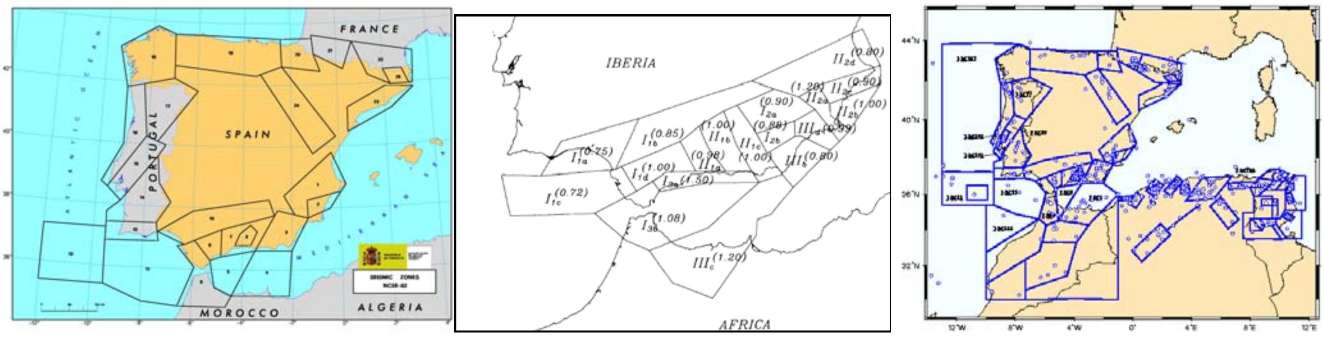
After of a careful revision of the proposed models of zones for Andalusia, we have considered three different seismic zonings: the one adopted in the Spanish seismic Building Code (NCSE-02), the model of López-Casado et al. (1995) (LC-95), and the model defined for the Global Seismic Hazard Assessment Project (GSHAP). The NCSE-02 model is composed of wide zones, which were defined based largely on epicenter distribution and main regional geological features on a Peninsula scale. LC-95 is composed by much smaller zones, which were defined based on relations found by the authors between the distribution of epicenters and fracture systems of the Betics. Finally, GSHAP is a model which combines zones from different countries: Spain, Portugal, Morocco and Algeria. These are the zones used for the hazard maps of the building codes of each country and their shapes are heterogeneous: the ones for Spain, Portugal and Morocco are extensive, while the zones of Tunisia are small and for Algeria the model includes zones and faults.

In order to obtain a first estimation of the impact that long-distance sources may have at long-period (T≥1.0s) spectral accelerations we have supplemented the Spanish models (NCSE-02 and LC-95) with other two defined for North Africa. The north African zoning have been chosen after a revision of the specialized literature, considering finally the zoning proposed by Hamdache (1998) (complemented with data of Peláez et al. 2006) and the one proposed by Aoudia et al. (2000) (hereafter noted as HAM-98 and AOU-00, respectively). Both zones have been considered as the more suitable for the next reasons. HAM-98 is a model for North Algeria based, mainly, in the tectonic of the region and the historical and instrumental seismicity and composes by 6 zones. The seismicity parameters have been obtained combining seismic, tectonic and paleoseismic information. The completeness of the catalogue has been also corrected. AOU-00 model covers the north of Algeria, NE Morocco and NW Tunisia and the boundary of the zones have been drawn with base in the knowledge of the active faults, the tectonic and cinematic of the big units, relationships between seismic structures and earthquakes and cluster patterns of epicenters.. Then we include 5 branches in the zoning node of the logic tree with these composite models: Model 1: LC-95 plus HAM-98 plus Zone12 of NCSE-02; Model 2: LC-95 plus AOU-00 plus Zone12 of NCSE-02; Model 3: NCSE-02 plus HAM-98: Model 4: NCSE-02 plus AOU-00; Model 5: GSHAP. The adopted models are shown in Figure 2.

On the other hand, the unavailability of strong-motion models for the study region makes it necessary to select from the literature other attenuation equations derived from statistically significant data sets and comprising wider magnitude and distance ranges. Two main criteria have been considered for selecting ground-motion models: 1) that they are derived from extensive databases with some tectonic affinity and 2) that the independent variable is given in terms of PGA and of SA for a wide range of vibration periods. The equations of Ambraseys et al. (1996) (AM-96), Sabetta and Pugliese (1996) (SP-96), and Berge-Thierry et al. (2003) (BT-03) on rock conditions have been chosen.

On the other hand, it is well known the different attenuation of the ground motions with source in the Azores Gibraltar zone. Existing attenuation laws in terms of macroseismic intensity (Martín, 1983; Molina, 1998) show that the attenuation is notably lower for this region than the corresponding to other parts of Iberia. In fact, the earthquakes with epicenter in this zone, as the 1755 or 1969 events, are felt in the whole Iberian Peninsula with a preferent propagation in NE direction, as reflected by isoseismal maps (Martínez Solares, 2001). We have used data of the M_w 6.1 12th February, 2007 and of the M_w 4.9 13rd December, 2004 events, occurred in the Azores-Gibraltar zone, both recorded in several accelerometric stations, in order to check other strong motion models and to choose the most suitable one (reflecting low attenuation) for simulating the attenuation of the motions with source in that zone. Affter a revision of different models, the ones derived by Tavakoli and Pezeshk (2005) (T&P05R) and Kanno et al. (2006) (K_06) are finally chosen because they are the ones which fit better with the data for short and long periods.

Finally, we will use combination of models, one for the continental part and other for the Azores –Gibraltar zone, considering the next options in hazard estimation: Model 1: AMB-96 plus T&P05 ; Model 2: AMB-96 plus K-06; Model 3: SP-96 plus T&P05 ; Model 4: SP-96 plus K-06; Model 5: BT-03 plus T&P05 ; Model 6: BT-03 plus K-06. The logic tree for the analysis is presented in figure 3.



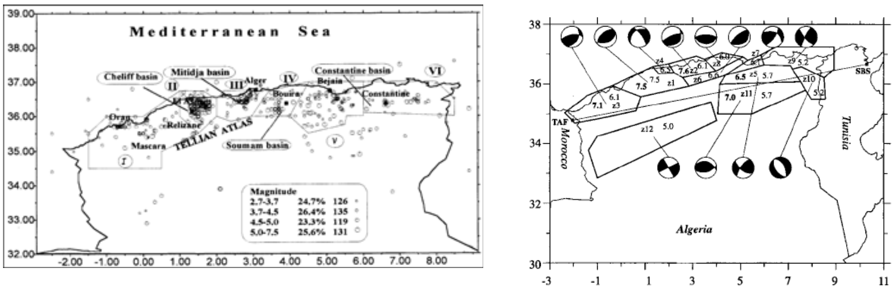


Figure 2. Seismic zoning models adopted in the study. From top left to bottom right NCSE-02, LC-95, GSHAP, HAM-98 and AOU-00.

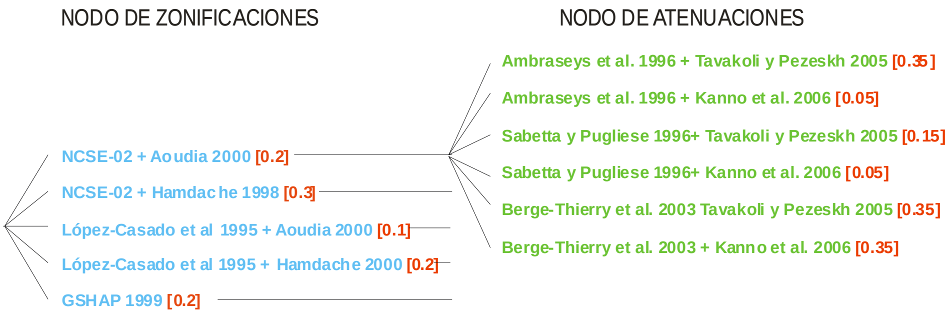


Figure 3. Logic tree for hazard estimation. The weight assigned to each branch is pointed out in brackets.

3.3. Estimation of Hazard and results (Rok sites)

We set up a logic tree consisting of two nodes: seismic source zoning and ground-motion attenuation model. Both nodes split into branches that stand for the combination of zonings and ground motion models presented in previous sections. Hazard calculations were carried out using the CRISIS code (Ordaz et al., 2001). The EXPEL tool (Benito et al., 2004) was used to visualize and manage the different 30 solutions stemming from the logic tree. A total of six hazard maps, corresponding to PGA and five spectral accelerations (0.1, 0.2, 0.5, 1.0 and 2.0 s) for rock conditions, were developed from a 0.1º x 0.1º grid. Figure 4 shows the hazard maps in terms of PGA, for return periods of 475 and 975 years representing in each case the weighted-mean acceleration values.

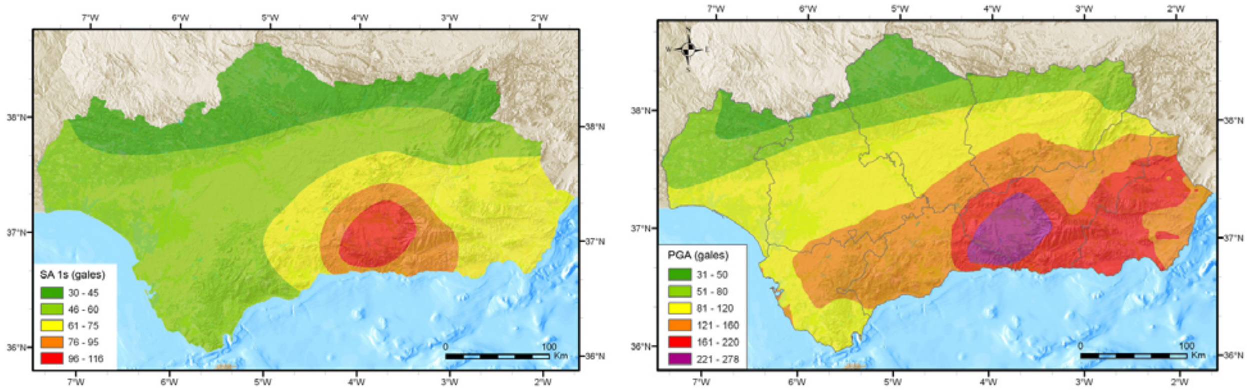


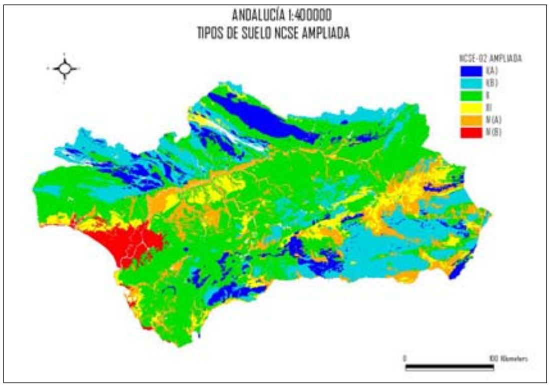
Figure 4. Hazard maps on rock conditions in terms of PGA for return period of 475 years (left) and 975 years (right)

Note that the expected PGA increase observed in the hazard map for 975-year return period is more significant in the areas where the expected PGA values for the 475-year return period are higher.

3.4. Hazard including site effects

The Andalusian region shows a great geological complexity, which leads to a variety of lithologies of different origins and characteristics and with a very heterogeneous distribution. In order to take into account the soil effect at a regional scale a geothecnical classification covering the entire territory was done and six soil types were distinguised, following the criteria exposed in Navarro et al (2009). The distribution of soil types and the corresponding amplification factors are shown in a zoning map (Figure 4) and the table 2, respectively. The map evidences the different dynamic behaviour from surface geological formations on the territory of Andalusia.

Seismic hazard including site effects has been estimated by the integration of results from previous phases. Seismic hazard maps at rock sites (Figure 3) have been superposed with the geotechnical classification map (Figure 4), applying the amplification factors over the values on rock conditions. Figure 5 shows these maps for PGA and return periods of 475 and 975 years. We can appreciate the different morphology of hazard areas between these maps and the previous ones in rock, as result of the strong influence of soil conditions in the expected ground motions. The largest expected PGA values are found in the Neogene basins of the Betics. Note that the areas with highest expected ground motions including site effects correspond to the areas with highest expected ground motions on rock conditions and not to the areas with expected highest amplifications. Moreover, areas with low expected accelerations on rock conditions present little influence of site amplification effects.



SOIL TYPE	PGA	SA (T)			
		0. 1 s	0.2 s	0.5 s	1.0 s
I(A)	0.87	0.84	0.80	0.80	0.80
I(B)	1.00	1.00	1.00	1.00	1.00
II	1.20	1.20	1.20	1.39	1.70
III	1.40	1.50	1.60	1.90	2.40
IV(A)	1.80	2.15	2.50	2.88	3.50
IV(B)	2.0*	2.25	2.5*	2.88*	3.5*

Figure 4. Geotechnical classification map of Andalusia (left) and soil-dependent amplification factors (right)

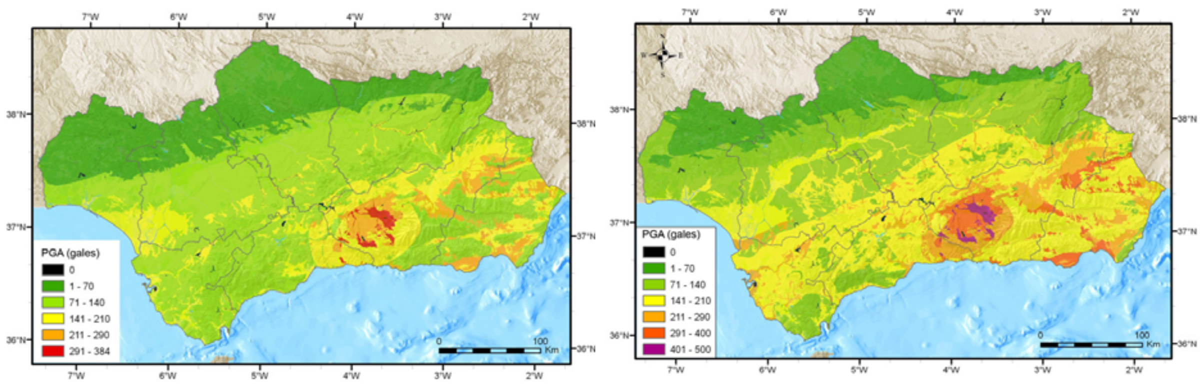


Figure 5. Hazard maps including soil conditions expressed as expected PGA for a return period of 475 years (left) and 975 years (right

3.5. Specific results in the capitals: Uniform Hazard Spectra and deaggregation analysis

In a last step some specific results have been obtained in the capitals of the eight Andalusian provinces.The uniform hazard spectrum (UHS) in each city was built “point by point” from the values of the spectral ordinates estimated SA (T) for T= 0.1, 0.2, 0.5, 1 and 2 s. Figure 6 (left) shows the resulting UHS (including local effect) for return period of 475 years. In addition a deaggregation analysis was carried out in each city obtaining the cells (M, D, ε) with higher contribution to the target motion given by the PGA value (derived from the previous hazard analysis) with return period of 475 years. The specific spectra (SS) for these control earthquakes, taking also into account the soil conditions in each city, were finally derived applying the ground motion models with a similar weight scheme than that used in the hazard analysis. Figure 6 (right) shows the results: SS and cells (M,D,ε) representing the control earthquakes in each city. The first remarkable observation is the elevated spectrum of Granada in comparison to the rest of the capitals. This is due to the confluence of the highest expected accelerations on rock conditions and a strong site amplification effect, and it is also reflected by the fact that the controlling magnitude for the given target motion at Granada is the highest of all cities. Furthermore, the resemblance between UHS and SS is notable, indicating the strong impact of local and relatively low-size sources on seismic hazard for the prescribed target motions (expected PGA for the 475-year return period).

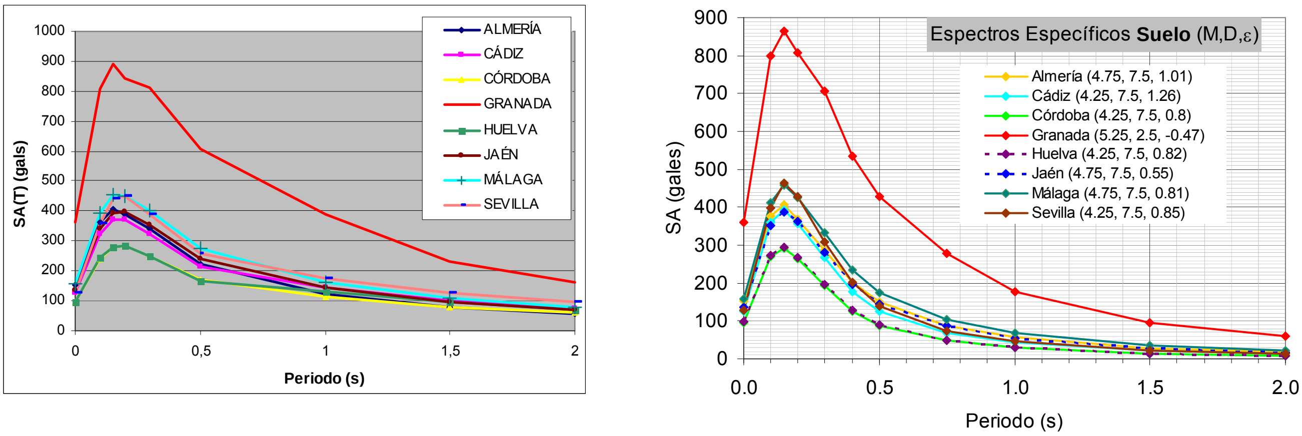


Figure 6. (Left) Uniform Hazard spectra (UHS) in the Andalusian capitals, for return period 475 years. (Right) Specific spectra for the control eartquakes (M,R, ε) obtained through deaggregation analysis for target motion given by PGA (475 years)

SUMMARY AND CONCLUSIONS

In a first step, seismic hazard maps in generic rock sites were developed for Andalusia in terms of PGA for return periods of 475 and 975 years. Values of PGA higher than 100 gals are present in the largest part of the territory; PGA exceeds 140 gals in some places of Granada, Almeria and Malaga provinces, while the highest values, PGA ≥ 200 gal, are presented in the Granada Basin. PGA decreases from the Internal Betics toward the Guadalquivir Valley and Sierra Morena range, where PGA becomes 25 gals. Similar patterns appear in the spectral acceleration maps, obviously with different values. Añadir comentarios sobre 975 años.

In a second step, a seismic-geotechnical classification into six categories has been proposed and seismic amplification factors have been determined for each class of soil. New hazard maps including local effects were obtained by combination of rock maps, seismic–geothecnical classification and soil amplification factors. The new hazard maps present PGA values in the range (24-370 gal) for the whole Andalusian territory, with highest expected values (PGA>300 gals) in some parts of Granada province and in Velez Malaga municipality. Lowest values PGA < 50 gales correspond to some municipalities of the north of Huelva and Cordoba provinces. Añadir comentarios sobre 975 años.
Añadir comentarios sobre los espectros

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