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Expected ground motion in the south-east of Spain due to an earthquake in the epicentral area of the 1910 Adra earthquake

José Morales[1,2,*], Belén Benito[3] & María Luján[1]
[1]*Instituto Andaluz de Geofísica and Prevención de Desastres Sísmicos Universidad de Granada, 18071 – Granada, Spain;* [2]*Departamento de Física Teórica and del Cosmos, Facultad de Ciencias, Universidad de Granada, Spain;* [3]*Escuela Universitaria de Ingeniería Técnica Topográfica, Universidad Politécnica de Madrid, Spain;* [*]*Author for correspondence; e-mail: morales@iag.ugr.es*

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Abstract

To study the ground motion level associated with historical earthquakes located in Southern Spain, we have chosen a scenario placed in the Poniente Almeriense (Southeast Spain). In this zone, some relevant historical earthquakes have occurred, such as those of 1522, 1804 and 1910. In particular, the earthquakes of 1804 and 1910 the estimated and calculated magnitudes are of M = 6.3. Those earthquakes took place near the epicentral zone of a seismic series happened in 1993–94. As part of this series, two earthquakes with M∼5 were recorded by strong ground motion instruments on 23rd December 1993, and 4th January, 1994 at Adra, Almería and Motril. We have used the acceleration records as empirical Green functions in order to simulate the expected ground motion associated with a hypothetical earthquake of magnitude M = 6.3 like those of 1804 and 1910. The simulations have been carried out for three sites (Almería, Adra and Motril) using three different approaches. A total of 30 simulations, for each approach, have been carried out for each ground motion component in each site. The peak ground acceleration (PGA) and the response spectra are compared with the values obtained through empirical relationships for the distances and soil conditions corresponding to the three chosen sites. The results of the simulations show that the horizontal PGA could exceed the values observed in 23/XII/93 and 4/I/94 by a factor of 5–8, surpassing in some cases the value of 140 gals. Besides, some of the peak spectral accelerations simulated reach Sa_{max} = 400 gals, Adra being the location where the highest values of a_{max} and Sa_{max} are reached, due to the nearness of this station to the epicentres of 23 /XII/93 and 4/I/94. At Almeria, the PGA values reach 40 gals, which may be considered as input in the bedrock. In Motril, the PGA surpass a value of 130 gals, considering as due to a strong local site effect. Finally, the peak ground acceleration (PGA) and the response spectra obtained with the simulations have been compared with other values estimated through empirical relationships for similar conditions. The conclusions about the expected ground motion levels have an important application aimed at the revision of the maximum acceleration and response spectra of the Spanish building Code, NCSE-94.

Introduction

Southern Spain is the zone with the highest seismic hazard in the Iberian Peninsula, as is shown in the maximum horizontal acceleration map for a return period of 500 years (Seismic Building Code, NCSE-94, 1994). The NCSE-94 use the Cornell (1968) zonated probabilistic method implemented through the EQ-Risk (McGuire, 1976) program, starting on the definition of 25 seismogenic zones in the Iberian Peninsula. The seismicity is considered as homogenously distributed in each zone, following a Poisson model, obtaining the characteristic parameters: maximum and minimum intensity, and the *a* and *b* parameters of the Gutenberg-Richter law. The NCSE-94 doesn't take into account individual faults in the contribution to the seismic hazard.

The contribution of seismicity to the hazard is a consequence of a regional lithosphere collision between the Euroasiatic and European plates. The interference of the Iberian microplate as well as the co-existence of compressional and extensional tectonics complicate the understanding of the collision, and many aspects of the tectonic structure and development of the region are still a matter of debate. The release of seismic energy creates a diffused seismic pattern in this plate boundary and consequently, the seismicity band in a longitude range (0° E – 6° W) may reach more than 400 km broad between the Iberian and African limits. On a time scale, the seismicity is characterized by a high microseismic activity rate $M \leq 4.5$, with less frequent earthquakes of moderate magnitude $4.5 \leq M \leq 6.0$, located in certain specific nucleus (i.e Granada basin, Málaga, Almeria, etc.), which have generated important damages.

In the past, the Poniente Almeriense region (Southern Spain) has suffered important earthquakes with a high level of damage in some cities and villages. As examples of historical earthquakes which have caused great loss, we can point to those of 1487, 1522, 1658, 1804 and 1910 with locations near Almería. The 1522 earthquake was especially important, because it completely destroyed the city of Almería and caused serious damages in an extensive area, which would mean that the associated magnitude must be moderate to high. On the 24th August 1804, another destructive earthquake in the Poniente Almeriense took place. Dalias was the village with the highest level of damages (I=XI), where all the buildings were destroyed and 267 people died. (Vidal, 1986).

Ibáñez et al. (2002) analyse the macroseismic data of historical and contemporary earthquakes, in order to estimate magnitudes for these destructives earthquakes in Southern Spain. The estimated magnitudes for the 1487 and 1522 earthquakes are 6.2–6.7 and 7.3 $\pm$ 0.3 respectively. On the other hand, the study of Ibáñez et al. (2002) also gives a magnitude of 5.7–6.0 for the 1658 earthquake and of 6.3 ± 0.3 for that of 1804. It is interesting to note that even being earthquakes of moderate magnitudes, these events are able to produce a relatively important damage level.

In the XX century, the earthquake with the largest instrumental magnitude in Southern Spain was recorded in 1910, with the exception of the very deep 1954 earthquake, whose moment magnitude is $M_w = 7.9$. The 1910 earthquake which had a magnitude of $m_b = 6.3$ (Karnik, 1969) and was located by Vidal (1986), off the coast of Adra, in 36.58° N and 3.08° W. The maximum intensity at Adra was VIII (MSK).

During the XX century other earthquakes and seismic series have taken place in the Poniente Almeriense, which point out the importance of the seismic activity in the region and the need for its study in order to obtain a more complete characterization of its seismic hazard and risk. In particular, in the last 20 years several events have taken place: one earthquake of $m_b = 5.0$ close to Sierra de Alhamilla in 1984 and a seismic series with two earthquakes of $m_b = 5.0$ and 4.9 in 1993 and 1994 respectively, both near the macroseismic epicenter of 1804 and the epicenter of the 1910 earthquakes.

It is clear that this region is a source of frequent moderate earthquakes and with certain frequency larger ones, such as those quoted for 1804 and 1910. Evidently acceleration records do not exist for these earthquakes but they determine in a decisive way the seismic hazard of the zone. For that reason the estimation of the ground motion associated with similar size earthquakes is of special interest. In fact, this seismic activity, characterized by moderate earthquakes and frequent microseismic activity is peculiar to the Mediterranean Basin, being also observed in countries such as Italy and Greece, where earthquakes with a magnitude of $6.0 \leq M \leq 7.0$ and high levels of intensity have taken place.

Characteristics of the 1993–94 seismic series in the Poniente Almeriense

Permanent stations in the region installed by the Instituto Andaluz de Geofísica y Prevención de Desastres Sísmicos (I.A.G.P.D.S.) and the Instituto Geográfico Nacional (I.G.N.) since 1983, has allowed us to locate the earthquakes and microearthquakes with good precision before and after the Adra-Balerma series in 1993–1994. Most of the epicentres are located in a cluster to the south of Balerma while others are in the Berja-Adra zone (Figure 1).

The series began on December 23rd, 1993 with an earthquake of $m_b = 5.0$ located in a zone between the villages of Berja and Adra (36.77° N; 2.91 W) and with a maximum intensity of VII MSK). On January 4th, 1994 another earthquake with magnitude $m_b = 4.9$ took place, but its epicenter was located 26 km away from the previous one (Figure 1), in the Alboran sea, off the Balerma coast with coordinates (36.56°N;

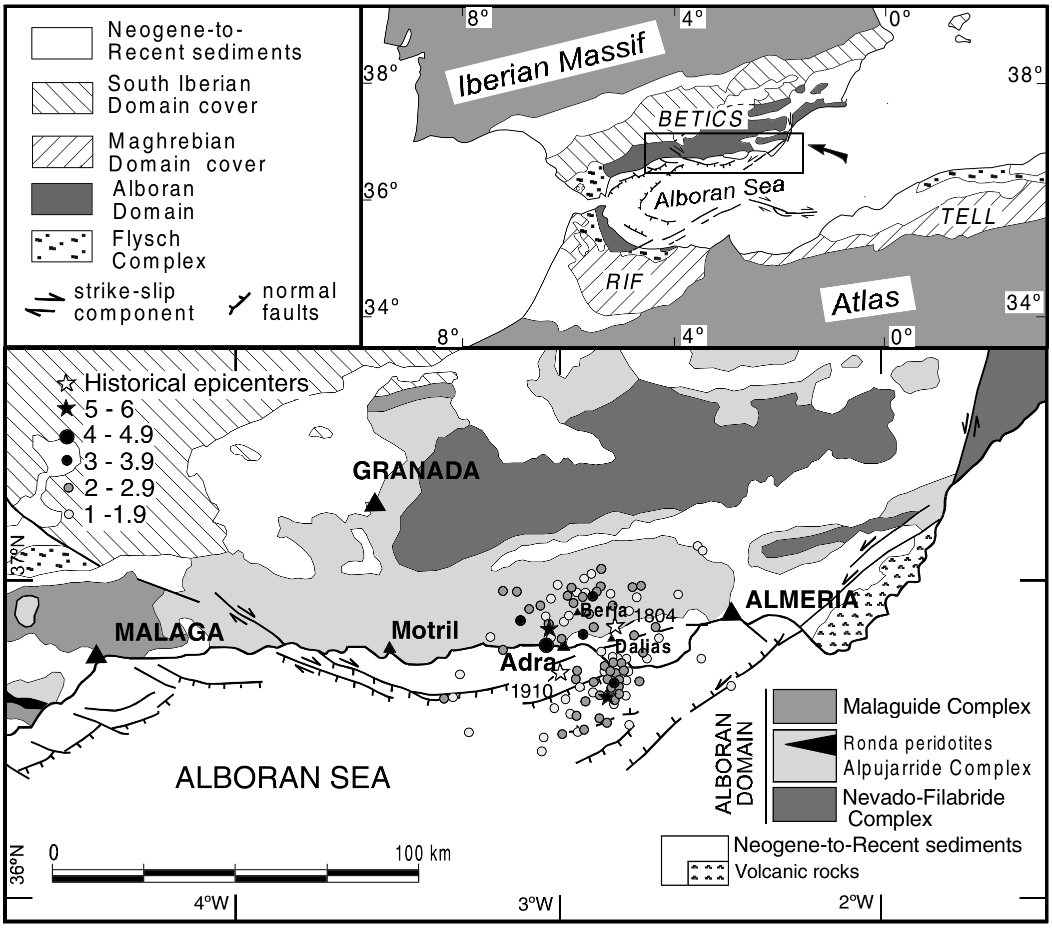


Figure 1. Map with the macroseismic epicenters of the 1910 and 1804 earthquakes (white stars). Earthquakes and microearthquakes recorded during the seismic series of 1993–94, as well as the location of the two main events (black stars): December 23 rd, 1993 and January 4th, 1994.

2°.80W). The maximum intensity was VII (MSK) and it was also followed by numerous aftershocks.

Analysis of strong motion records

The earthquakes on December 23rd and January 4th generated a set of accelerograms recorded by strong ground motion instruments deployed by the Instituto Geográfico Nacional (I.G.N.) in the epicentral zone and surrounding areas. The information contained in these records is very useful for the simulation of a future earthquake with a higher magnitude in the zone, which is the main objective of this work. For simulating the ground motion of both events we have chosen the accelerograms recorded in the stations of Adra (schists and quartzites), Almeria (Pliocene limestones), and Motril (alluvial sediments), which have been analyzed to obtain the source parameters (seismic moment and stress drop) for both earthquakes. These parameters are later used to obtain the scaling relationships between the empirical Green functions and the target earthquake to be simulated. The accelerograms analysed are shown in Figure 2 and some characteristics of them are shown in Table 2.

In the estimation of the Fourier source spectrum of the two events, temporal windows of 5 or 10 seconds of the horizontal components of the S wave have been used. The process for obtaining source spectra for the acceleration and displacement, $f^2\dot{M}o(f)$ and $\dot{M}o(f)$ respectively, is described as follows:

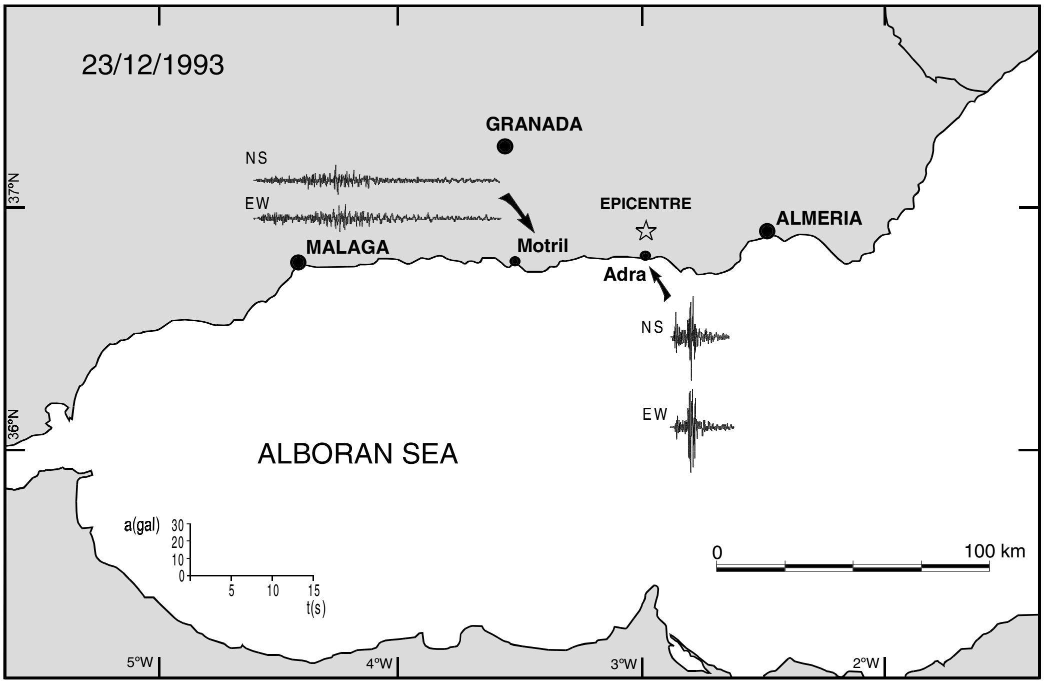
The Fourier acceleration spectrum a(f) is represented by:

$$a(f) = CS(f)G(R)\, e^{-\pi fR/\beta Q(f)}\, e^{-\pi\kappa f} \quad (1)$$

where,

$$C = R_{\Theta\phi} FP(2\pi)^2/4\pi\rho\beta^3 \quad (2)$$

and,



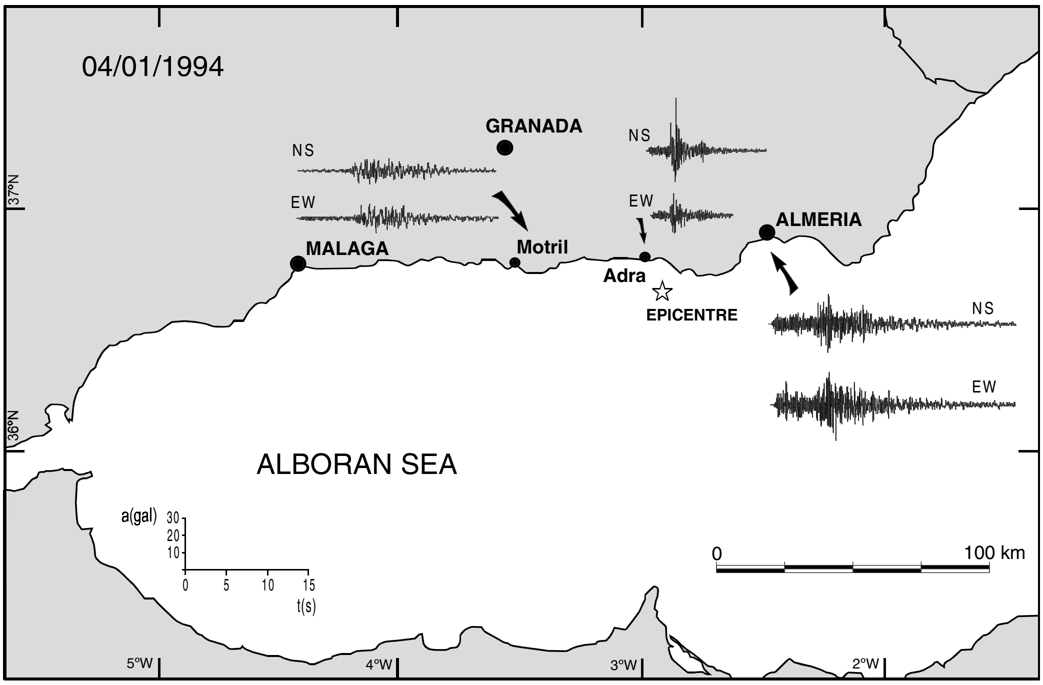


Figure 2. Horizontal components of the acceleration records corresponding to the December 23rd and January 4th earthquakes in the Adra, Almería and Motril recording stations.

Table 1. Peak Ground Acceleration, PGA, recorded for the strong ground motion accelerographs used in this work

Date (Epicenter)	Site	Epicentral distance (kms)	Comp. N-S Gals	Comp. E-W Gals
23-XII-93	ADRA	8	23.7	25
(Adra)	MOTRIL	48	17.3	14.5
04-I-94	ADRA	18	30	12
(Balerma)	ALMERIA	45	8.2	10.2
	MOTRIL	57	15.6	17.4

Table 2. Peak Ground Acceleration (average) of the ground motion. Simulation obtained with different methods

Green function	Station	PGA (gals) Component N-S			PGA (gals) Component E-W		
		J&B	OSA	W90	J&B	OSA	W90
23-XII-93	ADRA	79±12	117±24	170±35	97±14	140±37	186±49
23-XII-93	MOTRIL	72±12	90±19	127±30	81±13	105±18	125±21
4-I-94	ADRA	86±16	124±29	176±46	45±6	58±10	83±28
4-I-94	ALMERIA	37±7	43±12	60±13	33±7	40±6	55±11
4-I-94	MOTRIL	86±14	119±21	142±23	111±21	135±22	157±27

J&B = Joyner and Boore (1986) method.
OSA = Ordaz et al. (1995) method.
W90 = Wennerberg (1990) method.

S(f) is the source spectrum, which in the case of acceleration is written:

$$S(f) = f^2\,\dot{M}o(f) \qquad (3)$$

where $\dot{M}o(f)$ is the spectrum of the moment rate. If a model w^2 is assumed, as those proposed by Aki (1967) and Brune (1970), the source spectrum becomes:

$$S(f) = Mo\, f^2 fc^2/(f^2+fc^2) \qquad (4)$$

In the equations (1) to (4); R is the hypocentral distance, $R_{\Theta\phi}$ is the radiation pattern (0.55), ρ is the average density in the crust (2,67 gr/cm^3), β is the shear velocity (3.2 km/s), F is amplification factor due to the free surface (2), P represents the energy partition in the two components ($1/\sqrt{2}$), Mo is the scalar seismic moment, $f^2\dot{M}o(f)$ is the acceleration spectrum in far field and fc is the corner frequency. For a model of circular fault (Brune, 1970):

$$fc = 4.9\times10^6\beta(\Delta\sigma/Mo)^{1/3}$$

where β is given in km/s and $\Delta\sigma$ in bar.

In equation (1), the term G(R) corresponds to the geometric expansion of the wave front, which has been taken as 1/R for values of $R < 100$ km and as $1/\sqrt{R}$ for values of $R > 100$ kms. The Q(f) values have been extracted from Ibánez (1991), assuming that the attenuation is mainly due to scattering for Central Betic. The empirical term which represents attenuation at site is kappa 'κ' (Singh et al., 1982; Anderson and Hough, 1984).

With these considerations, the selected records were used for estimating displacement and acceleration spectrum at source, $\dot{M}o(f)$ and $f^2\dot{M}o(f)$ respectively for both earthquakes.

In Figure 3, the calculated displacement source spectrum for the 23rd December 1993 are shown. Such spectrum has been obtained from records of the Adra (R=8 km) and Motril (R=48 km) stations. Almeria did not record it. The best fit to the a w^{-2} source spectral model, gives the following source parameters: $Mo=2.5\times10^{23}$dyne-cm, fc=1.5 Hz and a $\Delta\sigma$ = 219 bars.

For the January 4th earthquake, we have chosen the accelerograms of Adra (R=18 km), Almería (R=45 km) and Motril (R=57 km). The displacement source spectrum for this earthquake is shown in Figure 3. The fit to the w^{-2} source spectral model provides the following parameters: a seismic moment

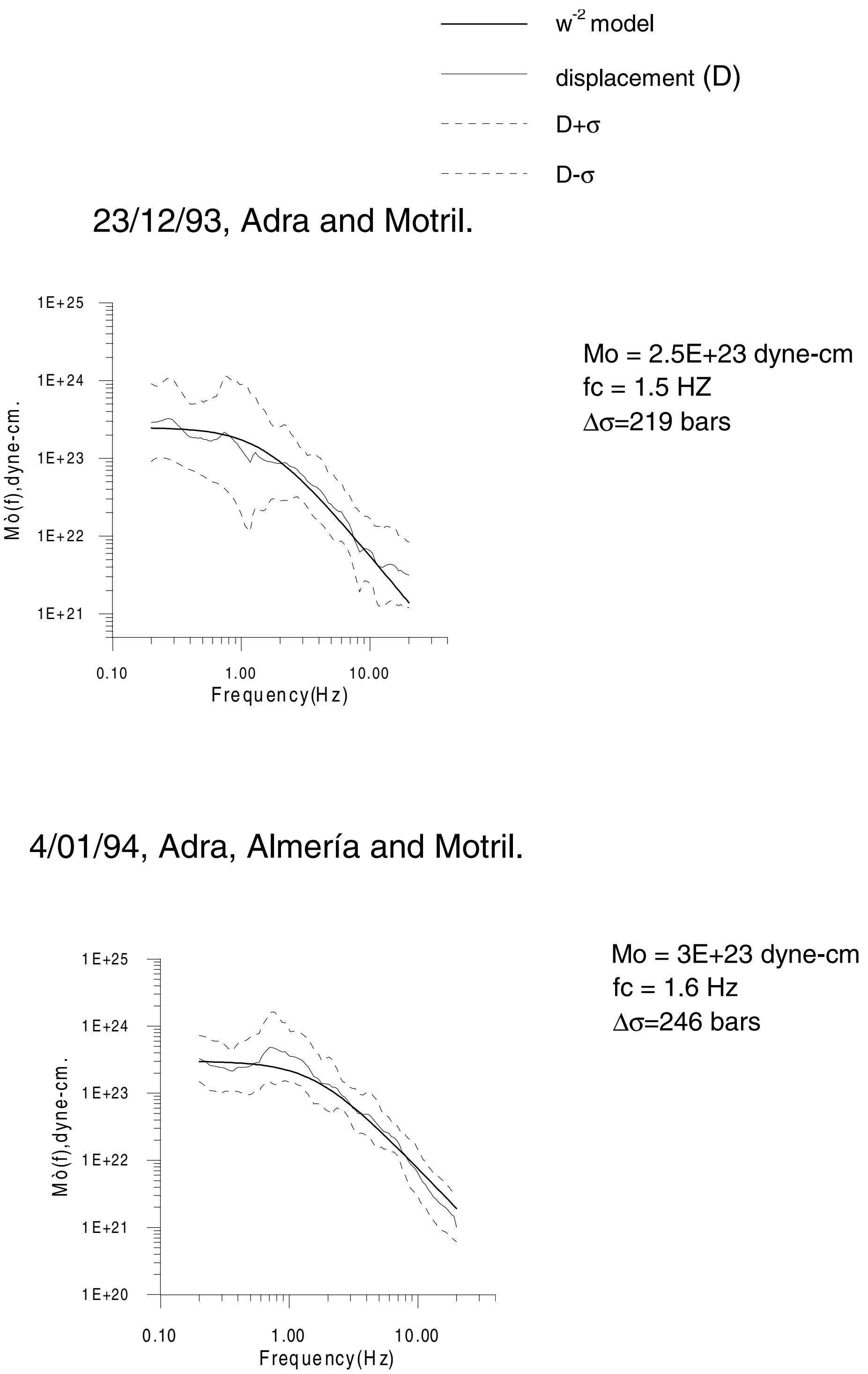


Figure 3. Average source displacement spectra as well as the spectral parameters of the December 23rd (above) and January 4th earthquakes (below).

of Mo=3.0×10^{23}dyne-cm, fc=1.6 Hz, and a $\Delta\sigma$ = 246 bars.

Expected ground motion of a future M = 6.3 earthquake using empirical green function

One of the most attractive methods to simulate time histories expected during a future large earthquake is called Empirical Green Function Method (EGFM), which is originally based on the work of Hartzell (1978). The advantage of this method is due to the fact that the information on source attenuation and local site amplification is included in the small records which are used as empirical Green functions. From the original paper of Hartzell (1978) the procedure of adding the empirical Green function has been improved in order to simulate 'realistic' ground motions (Irikura, 1983; Joyner and Boore, 1986; Wennerberg, 1990; Hutchings 1994, Ordaz et al., 1995; Jarpe and Kasemayer, 1996; Hartzell et al., 1999).

We have taken the accelerograms corresponding to the December 23rd and January 4th earthquakes as the Green functions to simulate the expected ground motion for an earthquake of magnitude m_b =6.3 similar to those in 1804 and 1910, choosing a seismic moment target of 2.5×10^{25} dyne-cm. We also considered that the focal mechanism of the earthquake to be simulated is equivalent to that of the Green functions and the source spectral model also follow the w^{-2} model, under the same conditions of stress drop.

The different simulation approach depends on the way in which Green's empirical functions are added to simulate the rupture process in the source (i.e Irikura, 1983; Joyner and Boore, 1986; Wennerberg, 1990; Zeng et al., 1994; Ordaz et al., 1995). In this work we present the time histories simulation using three different approaches for the adding of the Green's functions. These three methodologies are those given by Joyner and Boore (1986) (hereafter J&B) who, taking a source model w^{-2} both for Green's function and for the simulation, assume a random distribution in the delay time over the duration of a large event rupture. The second approach follows the method proposed by Wennerberg (1990) (hereafter W90) who, introduce a variation in the Joyner and Boore (1986) method and use a probabilistic distribution of the delay times. Finally, we also use the method proposed by Ordaz et al. (1995) (hereafter OSA) who, following the Wennerberg approximations, take a probabilistic density function to model delays in the adding of Green's functions.

For each method (J&B, W90 and OSA) we have carried out 30 simulations for each site (Adra, Motril and Almería) and component of the motion by using as empirical Green function the records of the two, December 23rd and January 4th events, obtaining in both cases the ground motion associated whit the expected M = 6.3 event.

Results

Time domain: PGA

As representation of the results obtained in the time domain, the acceleration time histories estimated with the OSA simulation are shown in Figure 4a. using as empirical Green function the records of the 23-12-93 earthquake and in Figure 4b. for records of the 4-1-94 one.

Table 2 shows the average peak ground acceleration, PGA, obtained in the simulations according to the different methods used. The values included have been estimated by averaging the 30 simulations carried out with each method for each site and component.

The methods assume the hypothesis that the Green functions are simulated in far field conditions, which is not realistic in the case of the December 23rd earthquake in the Adra station. In this case, the epicentral distance is of 8 km and, taking into account that the fault length for a M = 6.3 event may be of that order, this station should then be in near field. It is probable that the method used, assuming the hypothesis of far field, underestimates the high frequency accelerations in this station; while being conservative for large periods. In the case of the Green function associated to January 4th, the epicentral distance is 18 km in Adra, so that we could consider far field conditions.

The horizontal peak ground accelerations of the simulations are between 5–8 times greater than those observed in the earthquakes of 1993 and 1994, depending on the simulation method. In general, the J&B method gives horizontal PGA values smaller than the other two methods and, in turn, the W90 method gives the highest results. Considering that the most representative values for ground motion due to an earthquake similar to that of 1804 or 1910 are the intermediate ones obtained by the OSA method, the PGA values may reach 140 gals in the epicentral zone. The greater values would be obtained at Adra, for the simulations

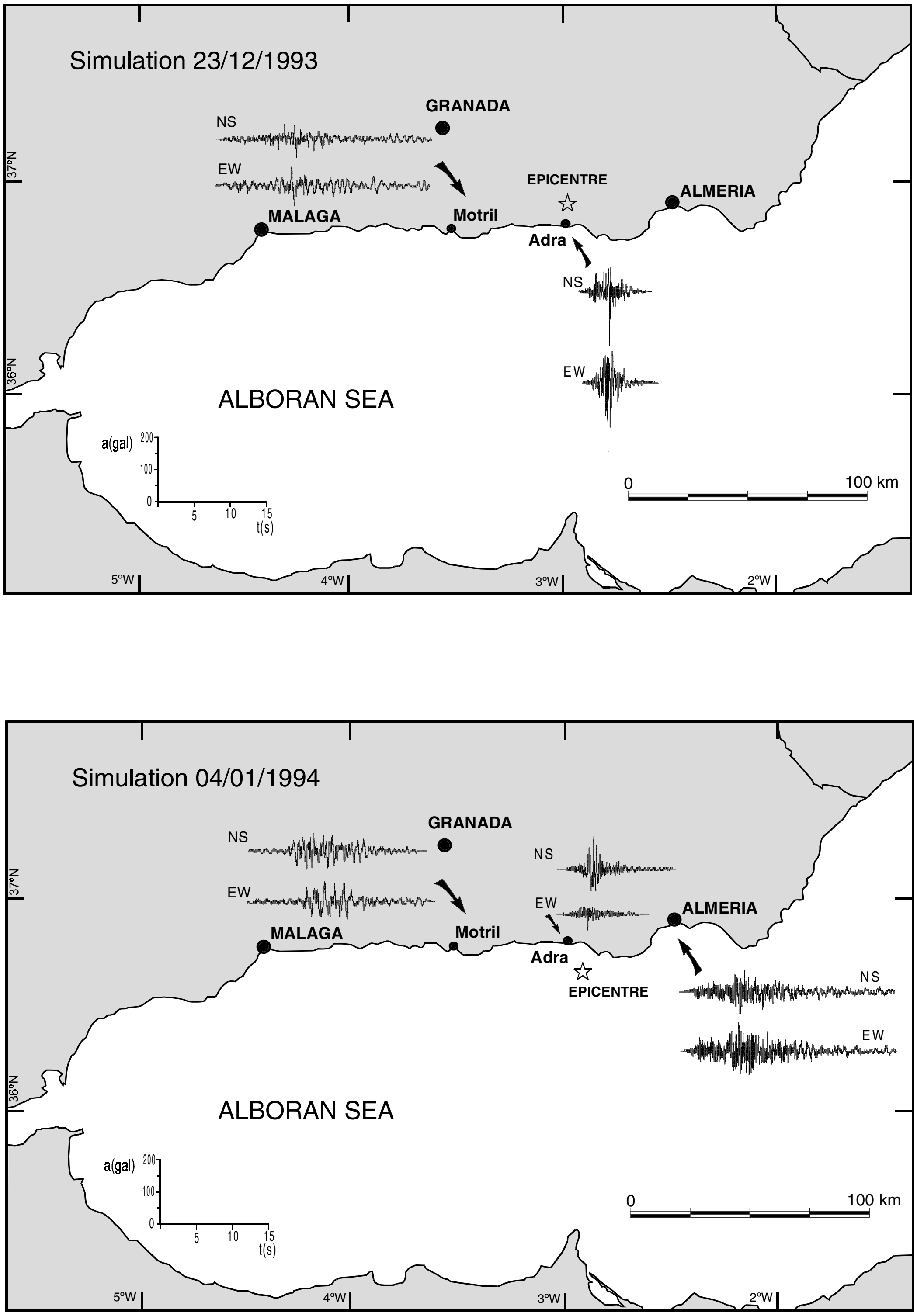


Figure 4. Simulation examples obtained with the Ordaz et al. (1995) method for sites in Adra, Motril and Almería using as empirical Green functions the accelerograms of the December 23rd (above) and January 4th earthquakes (below).

Table 3. Peak Ground Acceleration PGA (gal) empirically estimated with different strong motion models, in the same conditions as the simulation

Conditions of prediction			PGA (gal) predicted				
	Soil	Ep. distance	*Ambraseys*	*Sabetta*	*Tento*	*Dhale*	*Average*
23-01-1993 Adra	Hard soil S = 0	R = 8 km	226	339	380		315
23-01-1993 Motril	Soft soil S = 2	R = 48 km	57	56	69	82	66
04-01-1994 Adra	Hard soil S = 0	R = 18 km	107	150	177	249	171
04-01-1994 Almería	Hard soil S = 0	R = 45 km	46	60	72	89	67
04-01-1994 Motril	Soft soil S = 2	R = 57 km	49	47	59	66	56

Ambraseys – Ambraseys et al. (1996).
Sabetta – Sabetta and Pugliese (1996).
Tento – Tento et al. (1992).
Dhale – Dahle et al. (1990).

carried out both for the records of December 23rd and for those of January 4th too. At Almeria we would reach the smallest PGA, about 40 gals. At Motril the mean PGA given by the simulations surpass 100 gals (Table 2).

Comparison with empirical estimations

At the same time, in order to asses whether the maximum accelerations obtained by simulation are within the range of the expected values for the conditions of magnitude, M, distance, R, and soil, S, of the predicted motions, we have developed empirical calculations. For that purpose, we have used PGA relations as a function of these variables, M, R and S, inferred from the analysis of real data. The selected laws have been those proposed by Ambraseys et al. (1996), Sabetta and Pugliese (1996), Tento et al. (1992) and Dahle et al. (1990). All of them predict the horizontal peak ground acceleration (maximum of the two components) for one earthquake of a fixed magnitude, in our case M = 6,3, at a certain distance, which we identify with the epicentral distance for each simulation and in particular soil conditions, taken similar to those of the station recording.

The PGA values empirically inferred with each model are included in Table 3, where the average values, considering all models for the conditions of each simulation, are also included. It is convenient to note that the Dhale et al. (1990) model is only suitable for a distance range greater than 10 km; for this reason it has not been used in the case of the 23rd December earthquake in Adra, where the epicentral distance is of 8 km.

By examining Table 3, where the PGA given by the empirical estimations are shown, we can see that the highest values are obtained for Adra, in the simulation conditions done with the records of 23-12-93, which are on near field. According to these empirical estimations, on average we would reach values close to 300 gals, somewhat higher than those obtained in the simulations, around 140 gals with the OSA approach (Table 2). We also obtain moderately high values in this station for the conditions of the 4-1-94 earthquake, approximately 170 gal on average; somewhat higher than the mean obtained by simulation. Both the simulation methods and the empirical calculations give the highest PGA values in Adra for both shocks, something which can be put down to the shorter epicentral distance for this station.

In the other cases, (December 93 in Motril, and January 94, in Almeria and Motril) the maximum PGA obtained are quite similar, fluctuating around 60 gals, with the highest values given by the Dhale et al. (1990) model (Table 3).

To conclude, we can establish that the PGA simulated are smaller than ones empirically calculated with strong motion models from real data; even though in the case of the near field, the PGA obtained by simulation is significantly smaller which seems to confirm what we have already said: the method may underestimate the acceleration in these conditions.

Frequency domain: Response spectra

We have also obtained the response spectra for a critical damping of 5%, corresponding to the simulations for the two horizontal components. For each component we have applied the three approaches (J&B; W90 and OSA) and developed the spectra of the 30 simulations with each one. In order to illustrate the complete process followed, we show in Figure 5 the results obtained by the three methods for the December 23rd event at Adra station, component EW. Together with

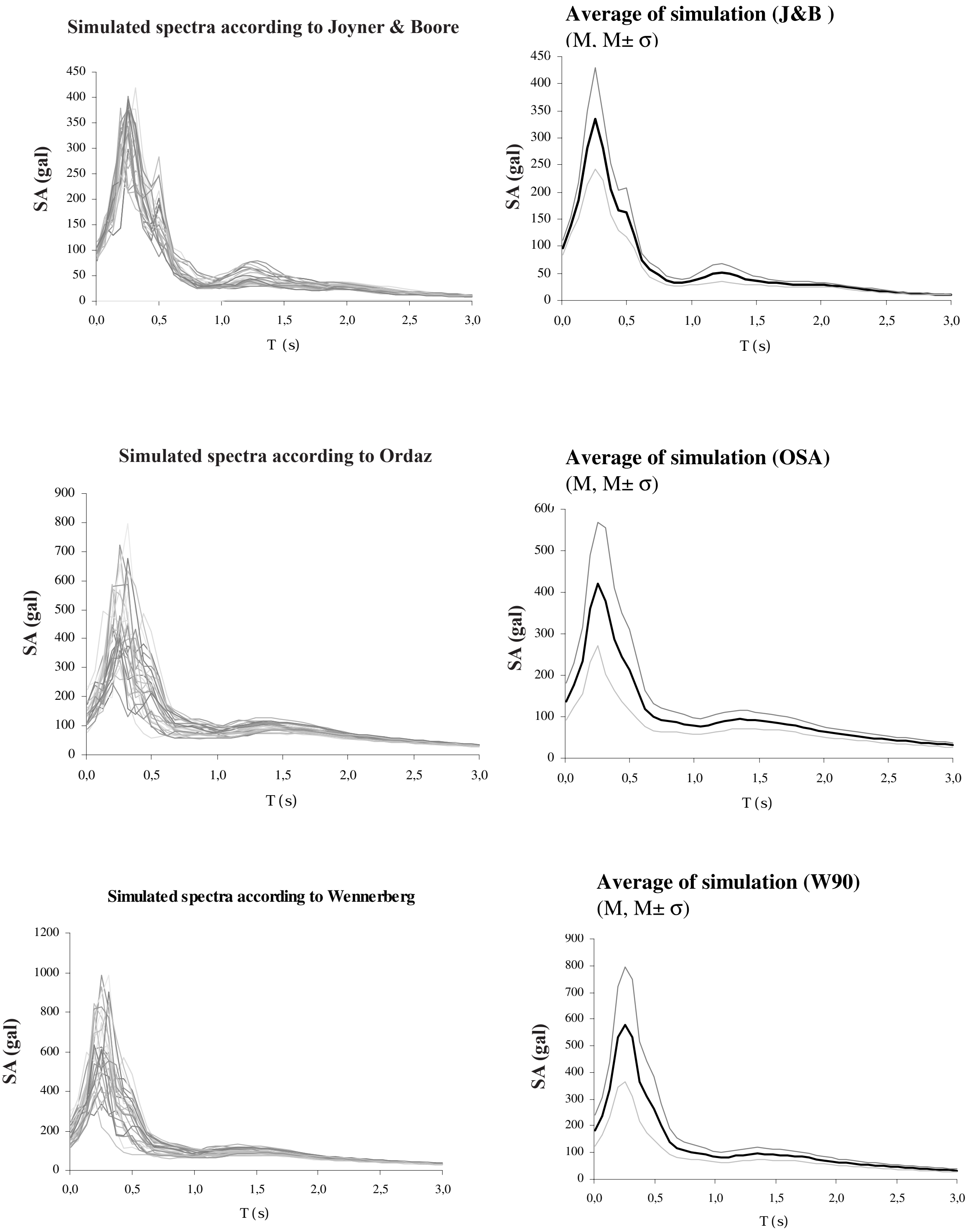


Figure 5. Left: Response Spectra Sa (5% critical damping) obtained by 30 simulations which each approach used in the work (J&B, W90 and OSA) in the following conditions: December 23[rd] event, EW component and Adra station. *Right:* Average response spectra (M) and M$\pm$ σ with each simulation method (σ is standard deviation).

the generated spectra the figure shows the average (M) and M$\pm\sigma$ spectrum for each method, where σ is the standard deviation.

It is possible to observe how the OSA method gives average results among all the ones estimated; for this reason we have chosen these results as representative of the simulations in all the cases studied. Taking this into account, Figure 6 shows the average M and M$\pm\sigma$ spectra obtained with the OSA method for the December 23rd event. The corresponding spectra for the January 4th event are included in Figure 7.

In every case the estimated spectra have been represented together with those proposed by the Spanish Building Code (NCSE-94) for the corresponding locations, in order to facilitate the comparisons and to establish conclusions as to whether our code is or not conservative in the face of an earthquake as the one expected in this study.

The analysis of figures including the comparison of spectra raises the following discussion.

The higher spectra correspond to the 23-12-93 earthquake in the Adra station, in particular for the EW component, where the maximum spectral amplitudes reach values over 600 gals, according to the W90 simulation (Figure 5). In any case, the maximum amplitudes in this station appear for periods of 0.2–0.3 s, and most of the spectrum energy is contained in the low period range, below 0.6 s. The spectral shape is typical of records in near field and bedrock, so that the simulation seems to respond quite well to both conditions. Moreover it is remarkable that the spectra obtained here exceed the one of NCSE-94, practically in the whole period range, which would lead us to question the latter code for earthquakes in the near field (Figure 6). On the other hand, considering the 4-1-94 records in this station, we obtain lower spectra, but which surpass 300 gals for the NS component and fit the NCSE-94 spectrum quite well (Figure 7); even though we must take into account that the epicentral distance is higher than in the previous case. Maximum amplitudes are also present for periods 0.2–0.3 s, and the spectral shape is not very different from that of other simulations in the same station.

In the Almería station, the estimated spectra show maximum amplitudes around 120 gals, also for periods of 0.2–0.3 (Figure 7). In this case, the NCSE-94 spectra have been represented for soil class as compact rock and we can appreciate that such spectra would be conservative for the whole period range.

In the Motril station, the spectra corresponding to both earthquakes and for the two components show quite a similar shape, with most part of the energy distributed in the range (0.5–1.5 s), without clearly predominant periods in this interval but also different vibration modes. The maximum spectral amplitudes are under 300 gals and the spectral shape obtained reflect the local effect event in this station, together with the large epicentral distances of 50–60 km. For the case of the December 23rd event, the spectra given by NCSE-94 in soil soft soil, cover the simulated spectra for all periods. However, the code spectra in the same station are exceeded by the ones simulated in the period range (0.5–1.5 s) for the January 4th event. It is convenient to point out that the local effect in this site seems well reflected by the simulations, given spectral shapes similar to those obtained directly from the real records of both events. Such effects may be responsible of the amplifications which are not being contemplated in the code, which doesn't seem conservative in this case.

Comparison with empirical spectra

In order to consider whether the response spectra estimated with the former procedure show amplitudes and spectral shapes typical of the characteristics of the expected motion at the sites, we have proceeded complementarily, to develop an empirical calculation such as we did for the PGA.

Thus, we have estimated response spectra using the models of Ambraseys et al. (1996), Sabetta and Pugliese (1996), Tento et al. (1992) and Dahle et al. (1990), always taking into account the suitability range of those models, regarding the class of soil, and the magnitude and distance ranges. For the Adra and Almeria stations, located in schist, quartzite and limestone, we have taken the models corresponding to hard soil or rock, considering a factor of S=0. The Motril station, located on alluvial sediments, belongs to the soft soil class, according to the classification of Ambraseys et al. (1996) and Sabetta and Pugliese (1996), with a factor of S=2.

The calculation has been done considering an earthquake of magnitude M = 6.3 and the epicentral distance corresponding to each of the simulations, as well as the soil class previously mentioned. The model of Dhale et al. (1990) has not been used in Adra for the December 23rd earthquake, because the epicentral distance of 8 km is beyond the covering range of the model.

The spectra empirically obtained have been represented together with the average simulated with the

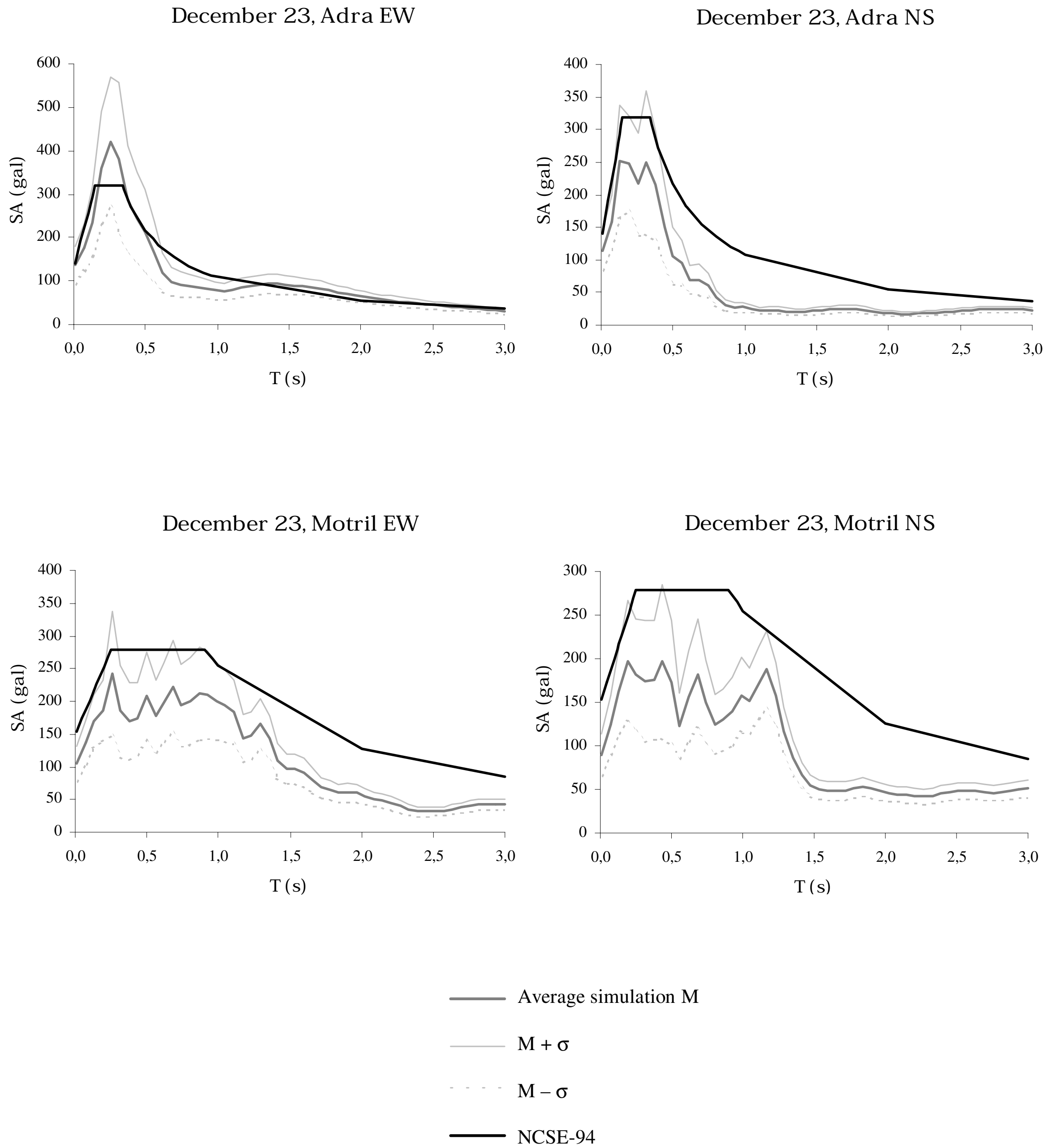


Figure 6. Response Spectra SA (5% critical damping) for the two horizontal components in each site, average and $M \pm \sigma$ of the 30 simulations with the OSA method, using the December 23rd earthquake records as Green functions. The results are compared with the design spectra of the NCSE-94 in Adra (hard soil) and Motril (soft soil).

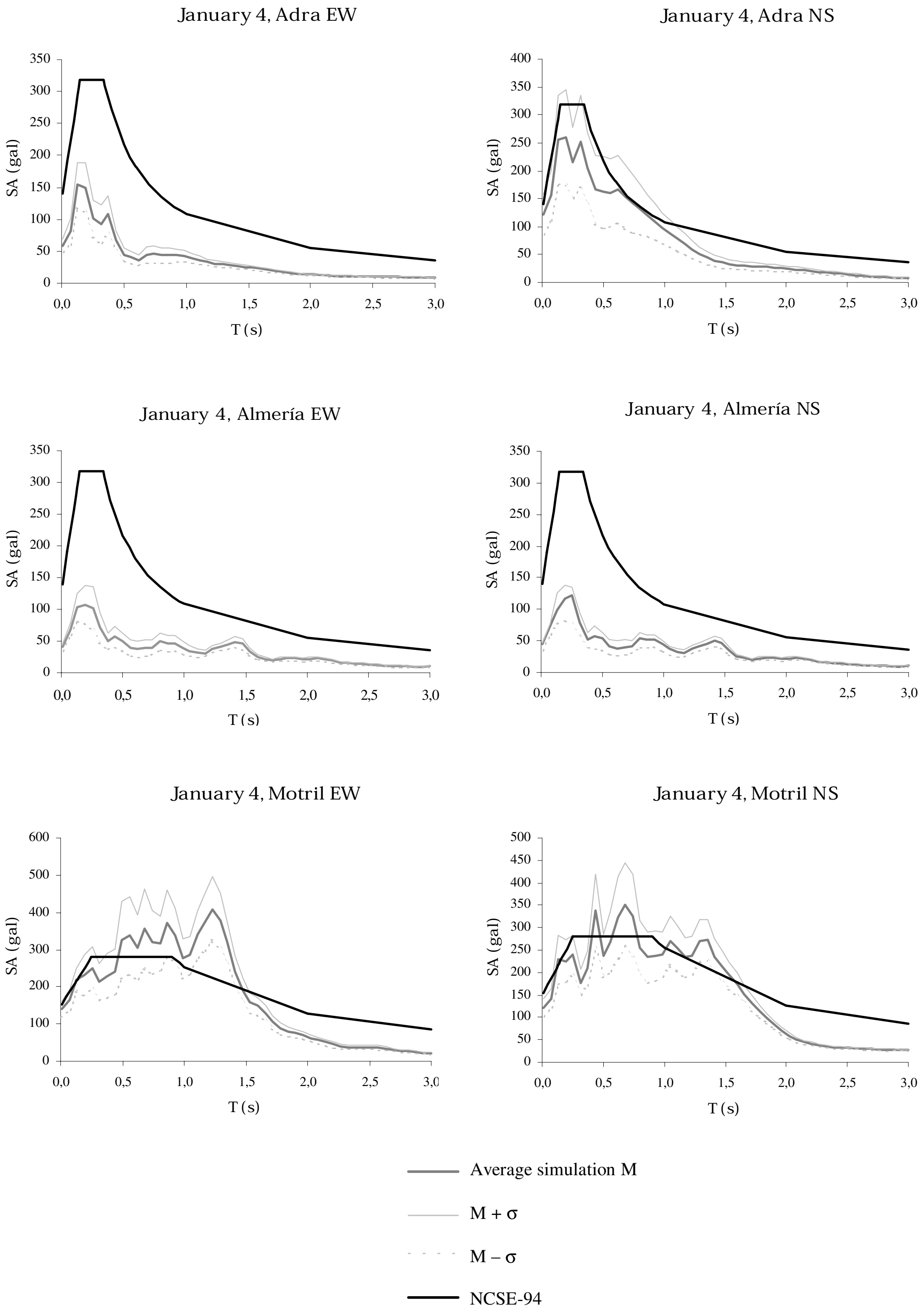
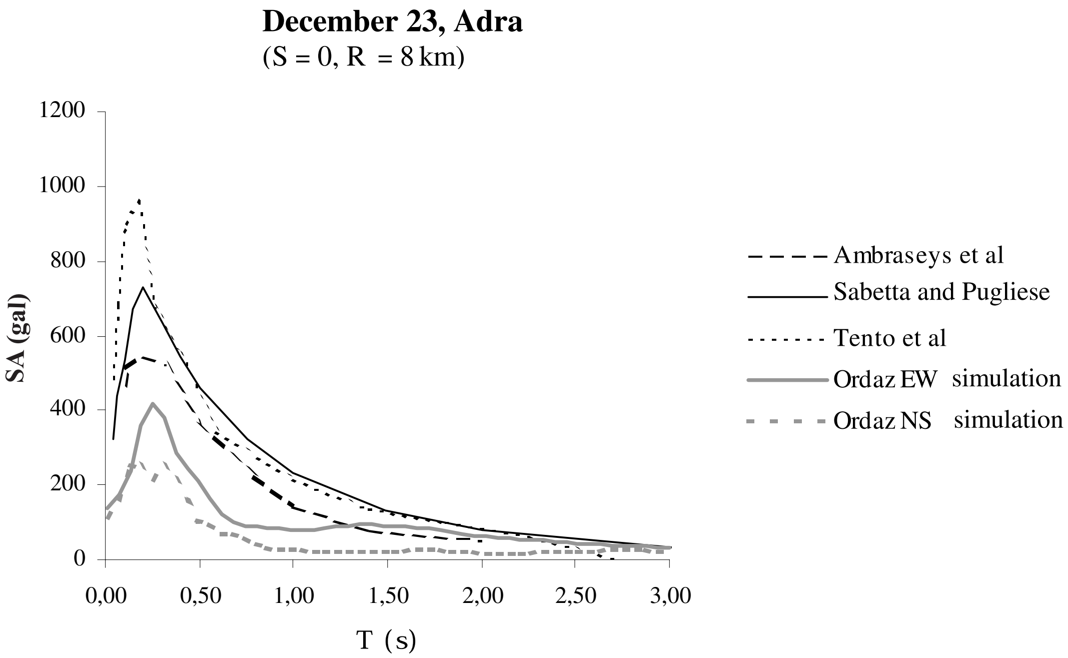


Figure 7. Response Spectra SA (5% critical damping) for the two horizontal components in each site, average and M$\pm$ σ of the 30 simulations with the OSA method, using the January 4th records as Green functions. The results are compared with the design spectra of the NCSE-94 in Adra (hard soil), Almería (hard soil) and Motril (soft soil).



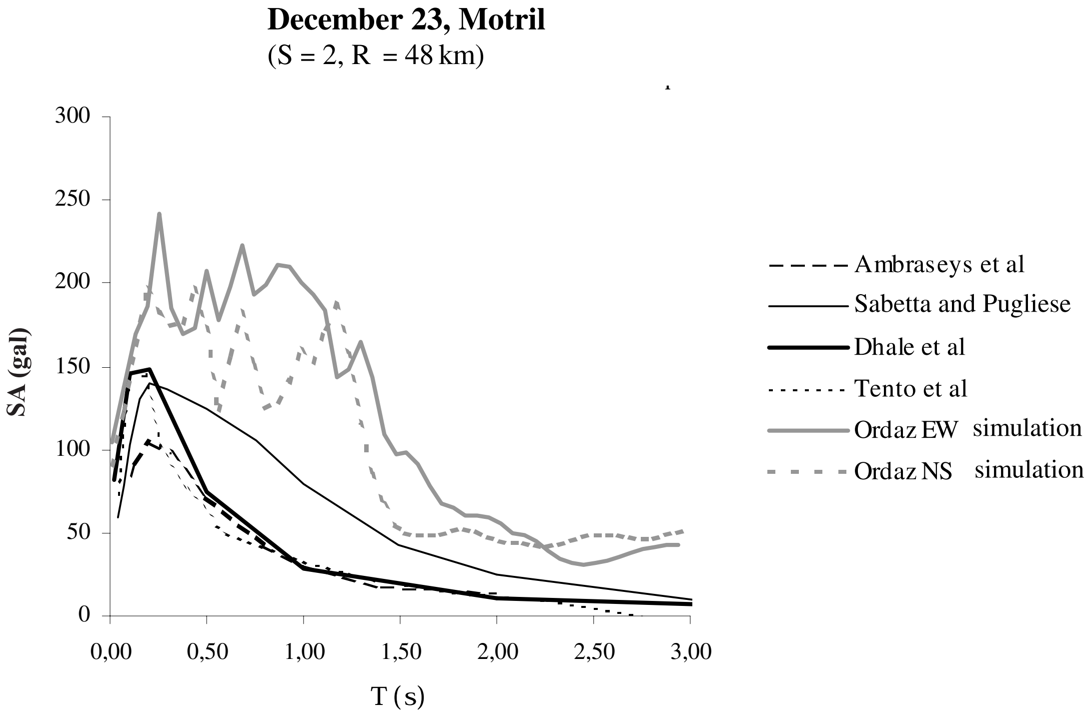


Figure 8. Response spectra (5% damping) empirically estimated with different strong motion models, for the simulation conditions of the 23-12-93 earthquake in Adra and Motril, along with the ones obtained in this study by the Ordaz et al. (1995) method.

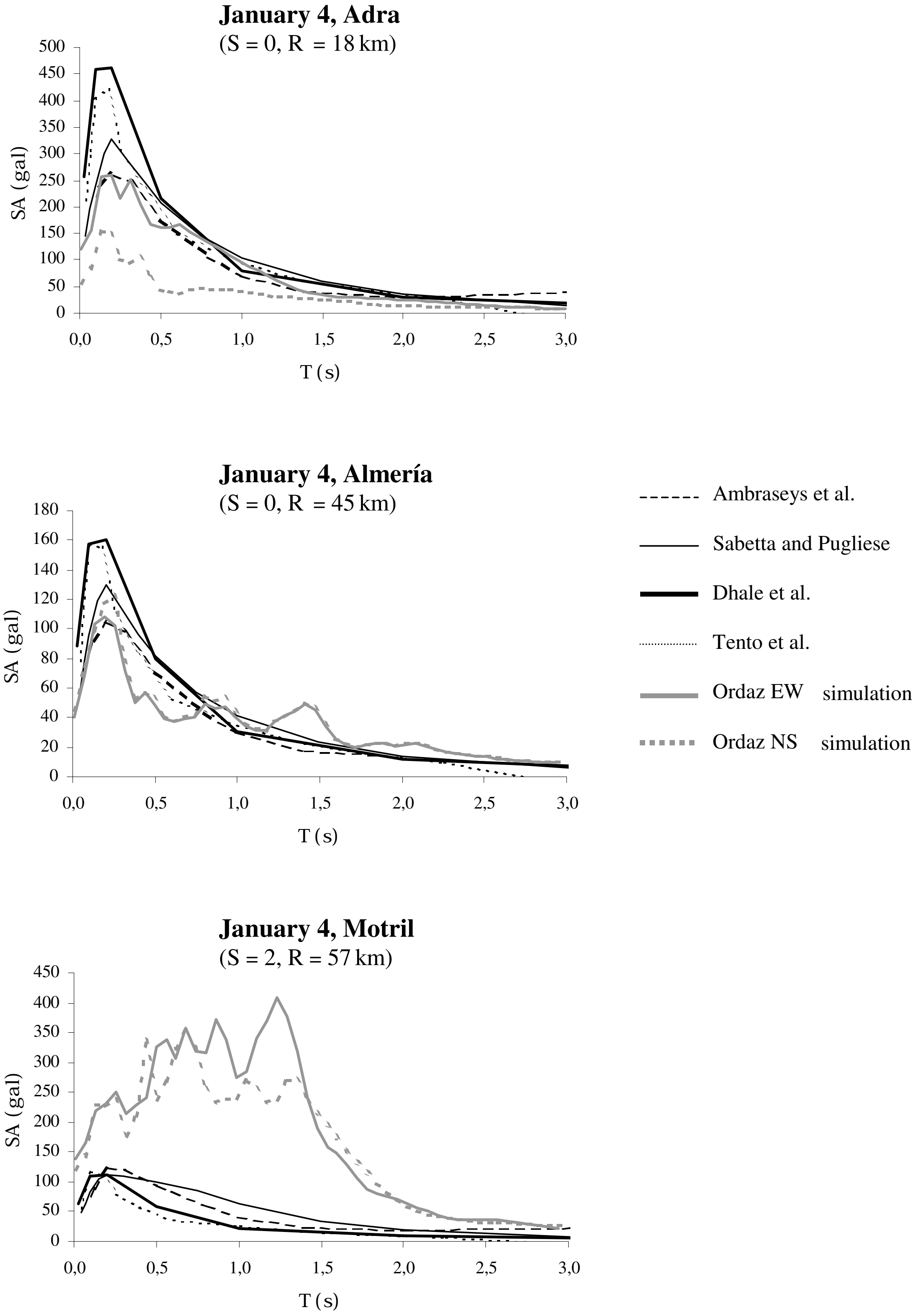


Figure 9. Response spectra (5% damping) empirically estimated with different strong motion models, for the simulation conditions of the 4-1-94 earthquake in Adra, Almería and Motril, along with the ones obtained in this study by the Ordaz et al. (1995) method.

OSA method, which in turn is an average of the spectra obtained with the three tested methods and the 30 simulations with each one. Figures 8 and 9 show the results of this comparison for the motion simulated from the records of 23-12-93 and 4-1-94, respectively. The analysis of these figures allows us to make the following comments.

Both types of spectra have quite similar shapes for the 1993 and 1994 earthquakes, in the two stations in hard soil, Adra and Almeria, while greater differences are observed in Motril for both earthquakes. The spectra simulated in Adra for the two earthquakes and for the two components are surpassed practically for all the periods by those empirically estimated with the different models; even though the maximum amplitudes in all of them are found in the same periods, around 0.3 s. The highest discrepancies between empirical and simulated spectra are found for periods of less than 1 s; the spectral accelerations being fundamentally different in this range, rather than the spectral shape.

Considering that the empirical spectra represent the average values of different records, the fact that they now surpass the simulated ones leads us to question the accelerations predicted by the simulation in this case. The possible underestimation of high frequency accelerations in the near field for the method followed in the simulation is once again revealed, and may explain the low estimated values in these particular conditions.

The empirical and simulated spectra present quite good agreement in Almeria, for the 4th January event. This is a case of study in hard soil at intermediate distance, where we find similar spectral shapes, and small differences in the estimated spectral acceleration, less than 60 gals.

In the Motril station, the spectra simulated for both earthquakes surpass the empirical spectra for the whole period range. Remarkable differences are found now for both earthquakes, so in the spectral shape as in the acceleration values. The simulated spectra reach values of about 200 gals for December 23rd and 350 gals for January 4th, in the period range (0.5–1.5 s), while those predicted are below 150 gals. This may be attributed to a clear site effect in this station best reflected in the simulation. In fact, as it has been already quoted, the spectral shapes obtained are similar to those directly derived from the records of the two events, although the amplitudes are now multiplied by a factor between 5 and 8, due to the change of magnitude from 5 (real events on 1993–1994) to 6.3 (hypothetical event considered in the study).

As a global result of the comparison, we may conclude that in those cases where no clear local effect is dominant, the spectral shapes simulated in this study are similar to the ones empirically calculated, which represent average values for the fixed conditions of magnitude, distance and soil, based on real data. There is good agreement in the predominant periods of motion, and in the case of intermediate distance and hard soil, the amplitude order of both kind of spectra is not significantly different. The highest discrepancies are observed in near field for low periods, and these differences may be put down to a possible underestimation of the spectral simulation in those conditions, due to the method used. On the other hand, the simulation in soft soil and at large distances provides spectra higher than the empirical ones for periods larger than 0.5 s, reflecting in an obvious way the local effect in these conditions. This result seems more realistic, if we compare the spectra with those obtained from real data

Conclusions

We have studied the ground motion associated with historical earthquakes occurred in Southern Spain. We have selected a region, the Poniente Almeriense, where destructive earthquakes took place as those of 1804 and 1910 with estimated and calculated magnitudes for both earthquakes around M = 6.3. In the same area a seismic series in 1993–1994 took place. During this seismic series two moderate earthquakes Mþ5.0 triggered strong ground motion accelerographs in the Adra, Almeria and Motril stations. The recorded accelerograms were taken as empirical Green functions, with the aim of modelling the expected ground motion for a hypothetical target earthquake similar to those which took place in 1804 and 1910, with a magnitude of Mw=6.3.

A total of 90 simulations were developed by three different approaches: Joyner and Boore (1986); Wennerberg (1990) and Ordaz et al. (1995), obtaining in each case the time history and the response spectra for the particular conditions of the simulation. A first analysis shows that the results with the Ordaz et al. (1995) method are average among all the simulations and these are taken as representative of our study. The obtained peak ground acceleration PGA may exceed those observed during the earthquakes of 23/XII/93 and 4/I/94 by a factor between 5–8. Moreover, in the ground motion simulated by a hypothetic event with a magnitude of Mw=6.3, the PGA may reach values around 140 gals in Adra, the highest estimated due to the nearness of this station to the epicenters of both earthquakes (8 and 18 km, respectively). In Almeria, with an epicentral distance of 45 km, the values of PGA exceed 40 gals slightly, which may be considered as input values in the bedrock, given that this site is located over limestone as part of its basement. In Motril, with epicentral distances of 48 and 57 kms and with soft soil conditions, the PGA reach values around 100–135 gals. In this case the PGA values are clearly dominated by a site amplification effect.

The response spectra obtained have been compared with those proposed by the Spanish Building Code NCSE-94, in order to evaluate if these are or not conservative, according to our results. The higher spectra obtained by simulation correspond to the 23-12-93 earthquake in the Adra station, where the maximum amplitudes appear for periods of 0.2–0.3 s and the spectral shape is typical of records in near field and bedrock. The spectra obtained here exceed the one of NCSE-94, practically in the whole period range, which would lead us to question the latter code for earthquakes in the near field. In the Almería station, the estimated spectra show maximum amplitudes around 120 gals, also for periods of 0.2–0.3 and the NCSE-94 spectra would be conservative for the whole period range. In the Motril station, all the spectra show quite a similar shape, with most part of the energy distributed in the range (0.5–1.5 s), reflecting a strong local effect. The maximum spectral amplitudes are under 300 gals and exceed in this range the ones of the building code spectra for the January 4th event. The local effect in Motril seems well reflected by the simulations, and may be responsible for amplifications which are not being contemplated in the code, by which it doesn't seem conservative in this case. On the other hand we have also developed empirical estimations using strong motion models and a final comparison has been done between the simulated and empirical amplitudes. As a global result, we may conclude that in those cases where no clear local effect is dominant, the spectral shape simulated are similar to the ones empirically calculated and in the case of intermediate distance and hard soil, the amplitudes order of both kind of spectra is not significantly different. The biggest discrepancies are observed in near field for low periods, and these differences may be put down to a possible underestimation of the spectral simulation in those conditions, due to the method used. The simulation in soft soil and at large distances provides spectra higher than the empirical ones for periods larger than 0.5 s, reflecting in an obvious and realistic way the local effect in these conditions.

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