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12th European Conference on Earthquake Engineering
Paper Reference 654

SIMULATION OF GROUND MOTION IN SOUTH-EAST OF SPAIN, USING STRONG MOTION RECORDS AND HISTORICAL INFORMATION.

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ABSTRACT

Southern and Eastern Spain are two of the regions with a highest seismic hazard in the Iberian Peninsula. The seismicity in these area during the past decades are characterized by an occurrence of earthquakes of moderate magnitude M<5.5; however some historical earthquakes become destructives and reached macroseismic intensity levels of IX and X. Then we have strong motion data recording during the past twenty years, corresponding to earthquakes of moderate magnitude, but we can expect the occurrence of bigger earthquakes in the zone which determine its seismic hazard. Therefore, it is important to develop some estimation of the associated ground motion combining the historical information with the instrumental data, which allows us to estimate the size and the source mechanism respectively. In this frame is found the subject of the present work, in which we develop an application to a scenario located in the Poniente Almeriense (Southern Spain). First, we have analyzed the historical information in order to estimate the maximun epicentral Intensities and the associated magnitudes in the studied area. Second, we have taken the strong motion records corresponding to recent earthquakes of magnitude 5 as empirical Green functions, aimed to simulate the expected ground motion associated to the hypotetic earthquakes as those historical in the zone. Then we have calculated the source parameters for the Green functions with the aim of obtaining the scaling relationships between these functions and the target earthquakes. And the simulations have been carried out using three different approaches: Joyner and Boore [1] Wennerberg, [2] and Ordaz et al [3]. 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 the distances and soil conditions corresponding to the records emploied. The conclusions about the expected ground motion levels have an important application aimed to the revision of the maximun accelerations and response spectra of the Spanish building Code, NCSE-94.
Key words: strong motion simulation; seismic hazard, Southern Spain

INTRODUCTION

South and Southern Spain is the zone with the highest seismic hazard in the Iberian Peninsula, as it is shown in the maximum horizontal acceleration map for a return period of 500 years, Seismic Building Code, NCSE-94 [4]. The contribution of seismicity to the hazard is a consequence of the litosphere collision between the Euroasiatic and European plates in a regional scale. In this process elastic strain is accumulated and relaxed though earthquakes and micro earthquakes. The liberation of seismic energy creates a diffused seismic pattern in the plate boundary without a clear alignement. As a consequence, the seismicity band in a longitude range (0 º E – 6 º W) may reach in extension more than 400 km between the Iberian and African limits. In 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. In this zone of frequent microseismic activity some earthquakes with bigger magnitudes occur from time to time, which produce important damages in certain locations of Southern Spain, reaching intensities of I >IX (MSK).

In particular, the Poniente Almeriense region (in Southern Spain) has suffered in the past important earthquakes with high level of damage in cities and villages. As examples of historical earthquakes which have caused great loss we can point those of 1487, 1522 and 1658, with locations near Almeria. On the 24 th august 1804, another destructive earthquake in Poniente Almeriense took place, with the highest damages in Dalias, reaching an Intensity level I=IX, Vidal, [5] .

Ibáñez et al. [6] analyze the macroseismic data of historical and contemporary earthquakes, with the aim of estimating magnitudes for these destructives earthquakes in Southern Spain. The estimated magnitudes for the 1487, 1522 and 1804 earthquakes are 6.2-6.7, 7.3 ± 0.3 and 6.3±0.3 respectively. In spite of their moderate magnitudes, these events are able to produce a relatively important damage level. Into the XX century, in June 16 th, 1910 the earthquake with the biggest instrumental magnitude in Southern Spain was recorded, with the exception of the 1954 earthquake with an extremely deep focus. The 1910 earthquake had an estimated magnitude of m_b=6.3 and took place in the Alboran sea, near the coast. This earthquake is therefore decisive in the seismic hazard of the region and for this reason the estimation of the possible associated ground motion is one of the main purposes of this study.

Besides the 1910 earthquake, during the XX century other earthquakes and aftershocks series have taken place. In particular, in the last 20 years several events have occurred 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 epicenters of 1804 and 1910, whose estimated magnitudes are 6.3.

It is clear that this region is a source of rather frequent moderate earthquakes with certain frequency and bigger ones, such as those quoted for 1804 and 1910. Evidently acceleration records don´t exist for these earthquakes but they determine in a decisive way the seismic hazard of the zone. For that reason the estimation of the strong ground motion which may be produced by similar earthquakes is of special interest, which involves developing the study of a hypothetic earthquake with a magnitude of 6.3 as the ones expected with a reasonable probability at zone.

CHARACTERISTICS OF THE SEISMIC SERIES 1993-94

The presence of 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 shocks and microshocks with good precision before and after of the Adra-Balerma series in 1993-1994. This series was preceded by a certain seismic activity in the zone. Since 1986 nearly 90 events have been recorded with magnitudes of 2.5 or bigger, in a radius of 30 km around Balerma. The most epicentres are located in a cluster to the south of Balerma while others are in the Berja-Adra zone (figure 1).

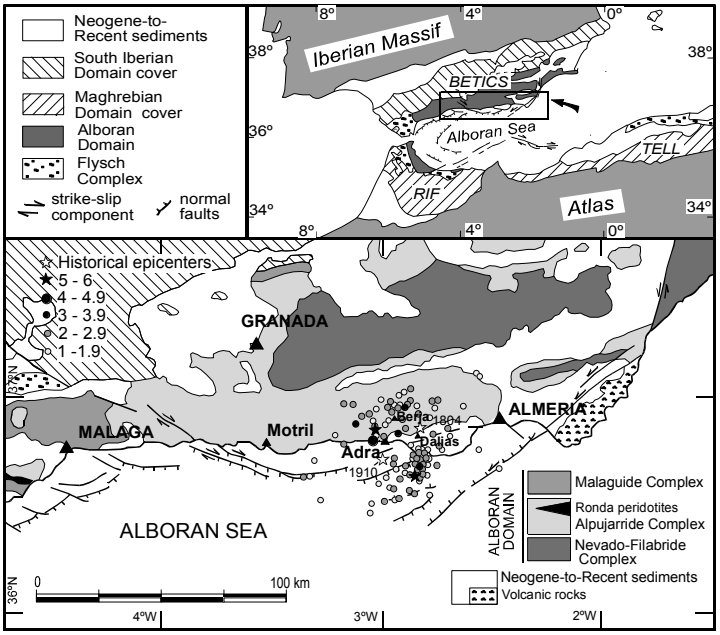


Figure 1.- *Situation Map with the macroseismic epicenters of the 1910 and 1804 earthquakes (white stars). Earthquakes recorded during the seismic series of 1993-94, as well as the location of the two main events (black stars): December 23 th, 1993 and January 4 th, 1994.*

The series began on December 23 th, 1993 with an earthquake of m_b=5.0 and a maximun intensity of VII (MSK) in the zone between Berja and Adra (36.77º N; 2.91 W), producing damage in both locations. This earthquake was followed by aftershocks in the same sector which followed one another until January 4 th, 1994. This day 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 (36.56ºN; 2º.80W). The maximun intensity was VII (MSK) and it was also followed by numerous aftershocks.

Stich et al [7] make the inversión of the source parameters concluding that the December 23 th earthquake is composed of three subevents with a focal depth of 8 km and the total seismic moment obtained for is of $2x10^{23}$ dinas.cm, which involves a moment magnitude of M_w=4.8. Similarly for the January, 4 th event , Stich et al [7] assign a focal depth of 6-8 kms and find the event composed by two subevents with a total seismic moment of Mo $=2.3x10^{23}$ dinas.cm , which is associated to a magnitude of M_w= 4.9.

ANALYSIS OF STRONG MOTION RECORDS.

The December 23 th and January 4 th earthquakes 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 bigger magnitude in the zone, which is the main objetive of this work. For simulating the ground motion of both events we have chosen the accelerograms recorded in the stations of Adra (schist and quarzcites), Almeria (Pliocene limestone) and Motril (alluvial sediments) which have been analysed with the purpose of knowing the source parameters (seismic moment and stress drop) for both earthquakes. These parameters are later used for obtaining the scaling relations between the empirical Green functions and the earthquake to be simulated. The accelerograms analyzed are shown in figure 2 and some characteristics of them are shown in table 1

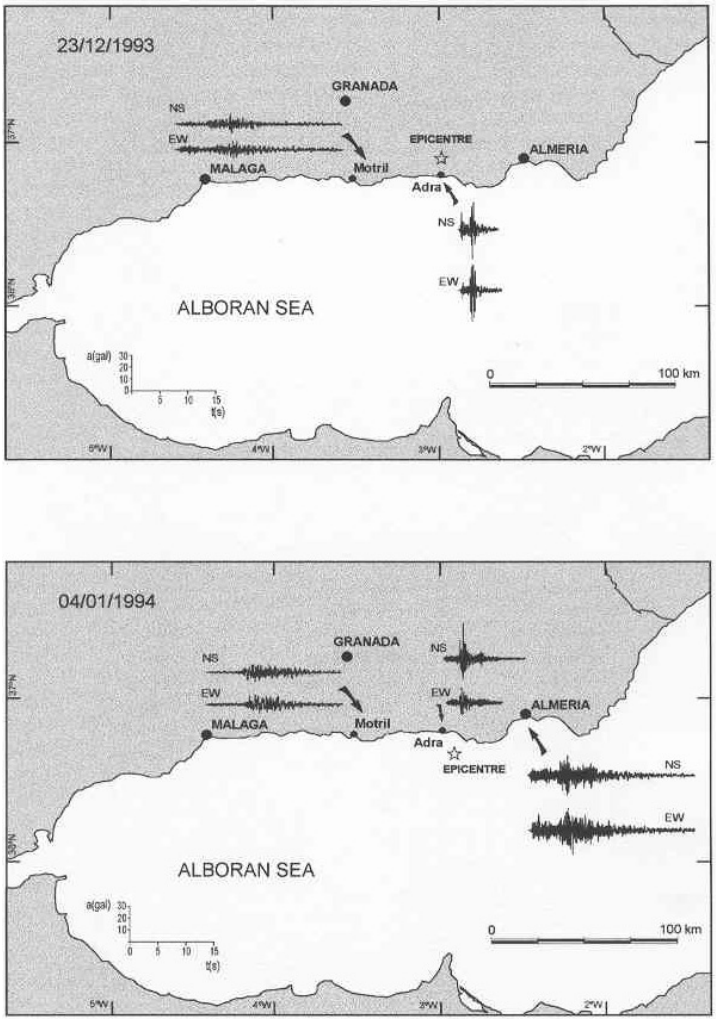


Figure 2.- *Horizontal components of the acceleration records corresponding to December 23 th and January 4 th earthquakes in Adra, Almeria and Motril recorded stations.*

TABLE 1
PEAK GROUND ACCELERATION, PGA, RECORDED FOR THE STRONG GROUND MOTION ACCELEROGRAPH USED IN THIS WORK.

	Accelerograph	Ep.distance(km)	PGA NS (Gal)	PGA EW (Gal)
23-XII-93	ADRA	8	24,2	25,9
(Adra)	MOTRIL	48	8,7	7,4
04-I-94	ADRA	18	30,5	12,4
Adra	ALMERIA	49	17	20,3
	MOTRIL	57	7	8,9

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, $f^2Mo(f)$ y $Mo(f)$ respectively, is extensively described by Morales et al. [8]

In figure 3 the estimated spectra of the source for the two parameters, acceleration and displacement are shown for the December, 23 th earthquake. Such spectra have been obtained from records of the stations nearest the epicenter of this earthquake, which are Adra (R=8 km) and Motril (R=48 km), given that Almeria didn´t record it. The best fit to the source spectral model, w^{-2}, gives the following source parameters: $Mo=2.5x10^{23}$dyne-cm. (in agreement with the result obtained by Stich et al [7] for the same shock) and a corner frequency fc=1.5 Hz. To fit the acceleration spectrum in high frequency, a Brune stress drop of $\Delta\sigma = 219$ bares is required.

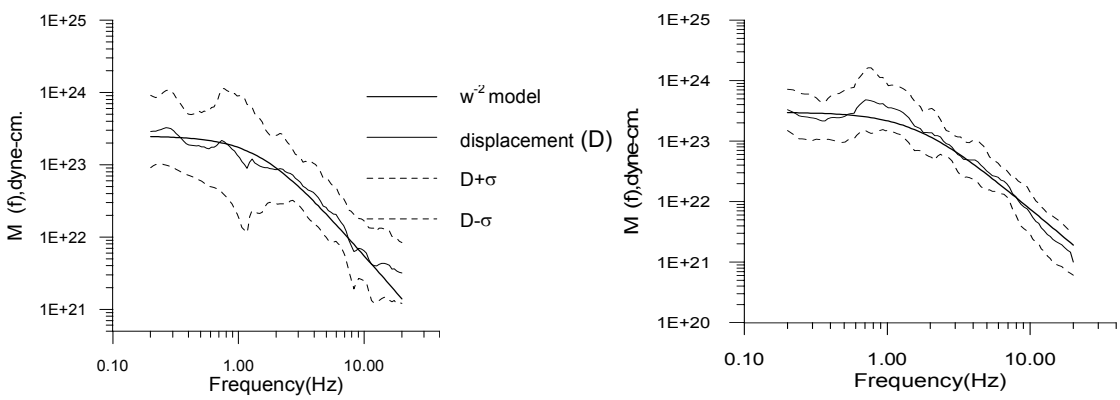


Figure 3.- *Acceleration and displacement spectra obtained through the spectral analysis from records of December, 23 (right) and January, 4 th earthquakes (left).*

For the January 4 th earthquake, we have chosen the accelerograms of Adra (R=17km), Almería (R=49 km) and Motril (R=57.5 km). The acceleration and displacement source spectra for this earthquake are shown in figure 3. The fit for the spectral model of the source w^{-2}, provides the following parameters: a seismic moment of $Mo=3.0x10^{23}$dyne-cm; a corner frequency of fc=1.6 Hz, and a Brune stress drop of $\Delta\sigma$ = 246 bares, so as to the high frequency spectrum.

EXPECTED GROUND MOTION OF A FUTURE M=6.3 EARTHQUAKE

There are different methods to simulate time histories expected during a future large earthquake, among them Kinematic-source modeling and composite source modeling (Joyner and Boore, [1]; Wennerberg, [2]; Ordaz et al [3]) are the two basic approximations used in the adding process of the Green functions to estimate the ground motion. The Kinematic source model requieres that the sum of the seismic moments of the subevents equal the seismic moments of the target event and in the composite source model the sum of the empirical Green functions are controlled by the scale relation between the small and the large earthquakes. In this last approach, we have taken the accelerograms corresponding to the December 23 th and January 4 th 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 y 1910, choosing a Mo target of $2.5 \cdot 10^{25}$dinas-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 is like w^{-2}, under the same conditions of stress drop.

In this work we present the time histories simulation using three different approaches for summing the Green functions. The first approach follows the model of Joyner and Boore [1], who taking a source model w^{-2}, both for the Green function and for the simulation, assume a random distribution in delay time over the duration of a big event rupture. The second simulation mode follows the method proposed by Wennerberg [2], who introducing a variation in the Joyner and Boore [1] method, and using a probabilistic distribution of the delay times, gives a more realistic aspect to the simulation. Finally, we also use the method proposed by Ordaz, et al. [3] who following the Wenneberg approximations, take a probabilistic density function to model delays in adding the Green functions. For each method we have carried out three simulations for each motion component, using as empirical Green functions those derived from records of the two events, December 23 th and January 4 th. In the first case we would be simulating the motion of an earthquake resembling the one of 1804 and, in the second case the one of 1910, whose magnitudes are the same.

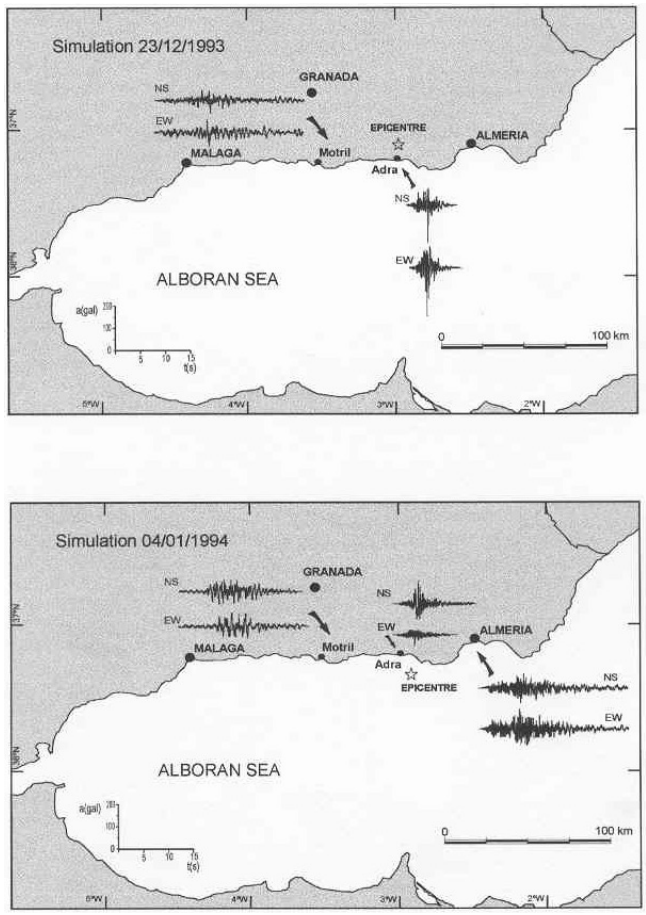
The acceleration time histories obtained with the Ordaz et al. [3] simulation are shown in figure 4a. for the earthquake of 23-12-93 and in figure 4b. for the other shock, of 4-1-94. Table 2 shows the maximum accelerations, PGA, obtained in the simulations according to the different methods used. The values included have been estimated averaging the three simulations done with each method.

TABLE 2
GROUND PEAK ACCELERATION (AVERAGE) OF THE GROUND MOTION.
SIMULATION OBTAINED WITH DIFFERENT METHODS

		PGA. (gals) Component N-S			PGA (gals) Component E-W			
Green F.	STATION	J&B	OSA	W	J&B	OSA	W	Average
23-XII-93	ADRA	88	150	257	110	216	297	186
23-XII-93	MOTRIL	36	60	80	42	74	74	61
4-I-94	ADRA	78	157	203	48	50	68	101
4-I-94	ALMERIA	65	108	155	81	100	120	105
4-I-94	MOTRIL	48	62	69	48	63	75	60

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

a)



b)

Figure 4.a,b - *Simulation examples obtained with the Ordaz et al (1995) method for sites in Adra, Motril y Almeria using as empirical Green functions the accelerograms of December, 23 (up) and January, 4 th earthquakes (down).*

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 23 th earthquake in the Adra station, where the epicentral distance is of 8 km. It is probable that the method employed, assuming the hypothesis of far field, underestimates the high frequency accelerations in this station; while being conservative for large periods. 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 Ordaz et al. simulation, the PGA values may exceed 200 gals in the epicentral zone.

At the sametime, in order to value wheter the maximum accelerations obtained by simulation are within the range of the expected values for the conditions of magnitude, M, distance, R and soil of the predicted motions, we have developed an empirical calculation, using PGA relations as a function of these variables, inferred from data of European earthquakes. The results are presented in detail by Morales et al [8]. In summary, we can establish that the simulated máximum accelerations are of the same order as the ones empirically calculated, 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.

We have also obtained the response spectra for a critical damping of 5 %, corresponding to the previous simulations for the two horizontal components. Figure 5 shows the average spectra estimated for an earthquake of magnitude M=6.3, using the records of 1993 in the Adra and Motril stations. Figure 6 includes the results of the simulated average spectra using the 1994 records in Adra, Almeria and Motril. In every case the estimated spectra have been represented together with those the ones proposed by the Spanish Building Code (NCSE-94) for the corresponding locations, in order to facilitate the comparisons and to establish conclusions on wheter our code is or not conservative in the face of an earthquake as the one expected in this study.

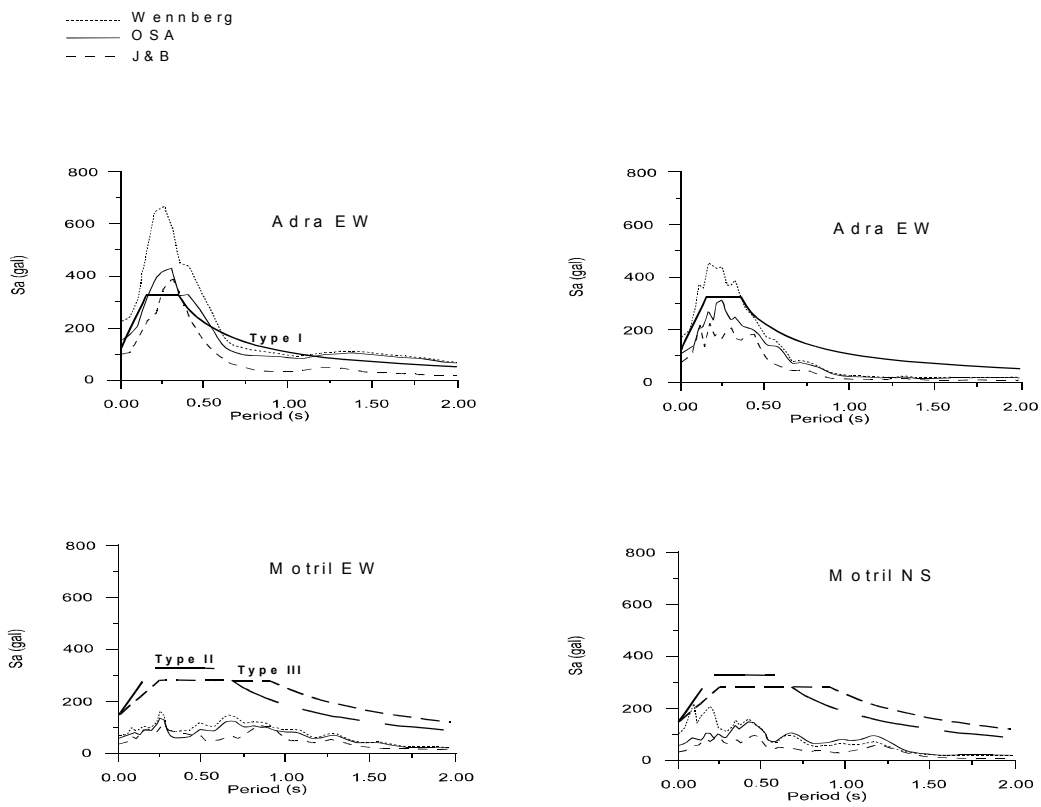


Figure 5.- *Response Spectra SA (5 % critical damping) for the two horizontal components in each site, average of the three simulations with the three methods, using the December, 23 th earthquake records as Green functions. The results are compared with the design spectra of the NCSE-94 in Adra (soil I) and Motril (soil II and III).*

The higher spectra correspond to the 23-12-93 earthquake in the Adra station, in particular for the EW component, where the maximun spectral amplitudes reach values over 600 gals. The spectral shape is typical of records in near field and rock, so that the simulation seems to respond quite well to both conditions. It is remarkable, besides, that the spectra here obtained exceed the one of NCSE-94, practically in all the period range, which would lead us to question the latter code for earthquakes in the near field. 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 quite well to the NCSE-94 spectrum. Maximum amplitudes are also present for periods 0.2-0.3s, and the spectral shape is not very different from that of other simulations in the same station.

In the Almeria station, the estimated spectra show máximum amplitudes around 300 gals, also for periods of 0.2-0.3 s and strong drop above 0.5s. In this case, the NCSE-94 spectra have been represented for a soil class I and II (compact rock, or medium to hard compacity). Considering the results obtained in EW component, the code spectrum would not be vey conservative for the low periods, smaller than 0.3 s.

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 (0-1,5 s), without clearly predominant periods in this interval. The maximum spectral amplitudes are under 200 gals and the spectral shape obtained reflect the local effect event in this station, together with the epicentral distances of 50-60 km. The spectra given by NCSE-94, both in soil II (intermediate) and soil III (soft), cover the others completely for all periods, for which reason they may be considered as conservative.

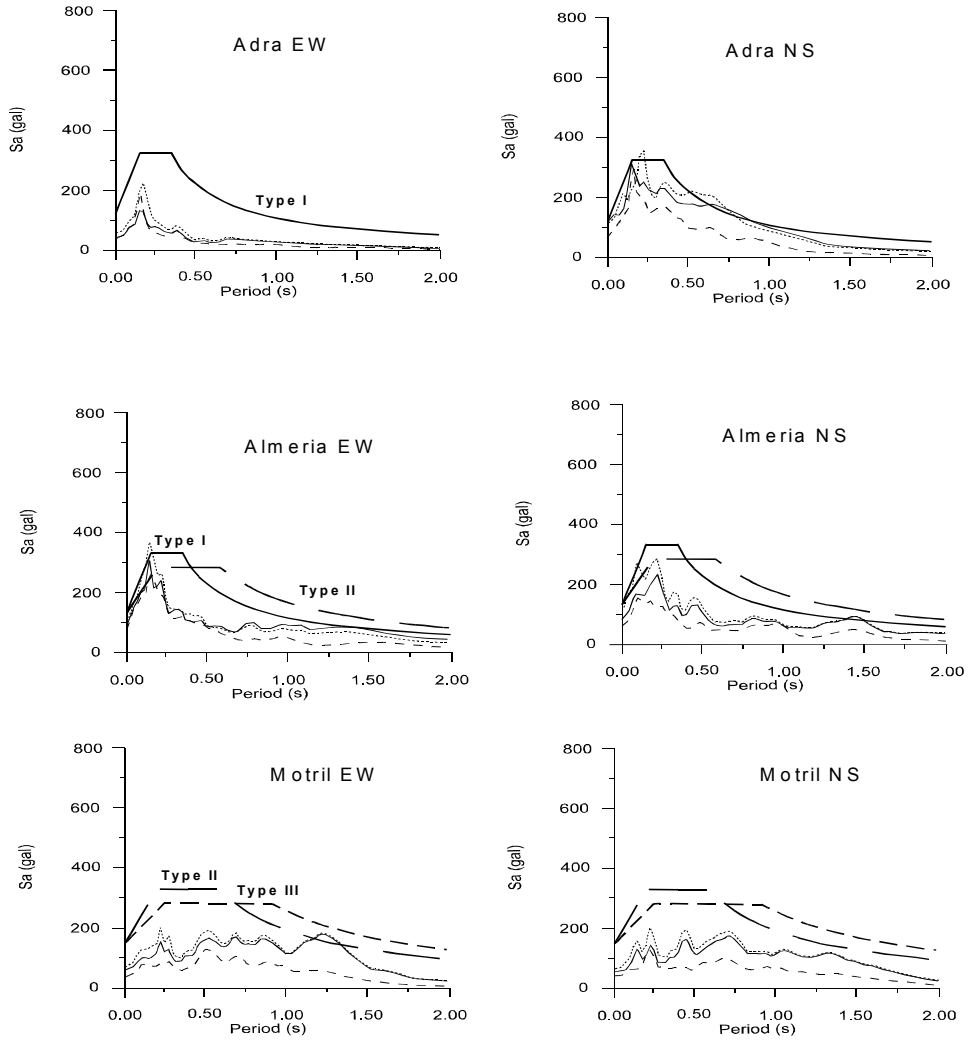


Figure 6.- *Response Spectra SA (5 % critical damping) for the two horizontal components in each site, average of the three simulations with the three methods, using the January, 4 th records as Green functions. The results are compared with the design spectra of the NCSE-94 in Adra (soil I), Almeria (soil I) and Motril (soil II and III).*

CONCLUSIONS

In the tectonic area where the seismic series of 93-94 took place, several earthquakes of high intensity, IX or X degrees in the MSK scale, have also occurred in the past time, revealing that the zone is one of the major seismic activity zones in the Iberian Peninsula, with important events to be noted in 1431, 1518, 1522, 1804 y 1910. Regarding the recent activity in the Poniente Almeriense, we have used the strong motion records of the main events belonging to the Adra-Balerma series of 1993-1994 in the Almería, Adra and Motril stations, in order to estimate the source spectra for displacement and acceleration. The results for the December 23 th earthquake concerning the source parameters are as follows: a seismic moment of $2{,}5 \cdot 10^{23}$dyne-cm and a stress drop of 219 bares; for the January 4 th shock the seismic moment estimated is $3 \cdot 10^{23}$dyne-cm, the stress drop is 267 bares, while the corner frequency is of the same order for both events: 1,5 and 1,6 Hz respectively.

The accelerograms were taken as empirical Green functions, with the aim of synthetizing the expected ground motion for a hypothetic earthquake similar to that which took place on 1910, with a magnitude of approximately M=6.3, similar in its turn, to that of 1804. The simulations carried out reveal that the horizontal PGA may exceed, by a factor of 10, those observed during the earthquakes of 23/XII/93 and 4/I/94. Besides, in the ground motion simulated, the PGA may exceed 0.2 g and some spectral accelerations (5 % critical damping) reach values around 0.7g. Adra is the station with the highest estimated values for PGA y Sa_{max}, due to its nearness to the epicenters of 1993 and 1994. In Almeria the maximum values of PGA exceed 150 gales, which may be consider as input values in the rock bed, given that this site is located over limestone as part its basement. Then, they would be minimum values. In Motril, with an epicentral distance of approximately 80 kms and soft soil conditions, the PGA exceeds a value of 60 gals, the site effect already included in the simulation.

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