# Deterministic Seismic Hazard Assessment for North Morocco

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**ABSTRACT:** *The purpose of this work is to evaluate the regional seismic hazard for Morocco, following the deterministic approach proposed by Costa et al [1], based on the computation of complete P-SV and SH synthetic seismograms. The input for the computations is represented by source and structural models. Seismic sources are parameterized using the knowledge about past seismicity and the tectonic regime. The regional structural model we adopted is the one proposed by Cherkaoui [2], modified in its shallower part to account for the effects of the uppermost sedimentary layers. Maps of peak acceleration, velocity, and displacements are used for the general representation of the hazard. Accelerations are in good agreement with the values determined by Jimenez et al [3] with the standard probabilistic approach.*

**Keywords:** Deterministic hazard modeling; Morocco; Seismic hazard maps; Synthetic seismograms

## 1. Introduction

Morocco, part of the North Africa plate, is at the boundary between the African and European plates. The seismic history mentions several important earthquakes distributed in the territory of the country. In particular, northern Morocco has been most affected by earthquakes in past. The last relevant one is the earthquake of 26 May 1994 of magnitude 5.9 which caused great damage in Al Hoceima city and the surrounding area [4, 5].

Various studies have been performed in the past to evaluate the seismic hazard in Morocco. Recently, Cherkaoui [2], Tadili [6] and Jimenez et al [3] have calculated the seismic hazard of Morocco using probabilistic approaches [7].

In this study, we compute the seismic hazard in the country using the deterministic approach developed by Costa et al [1], based on the computation of complete synthetic seismograms.

## 2. Deterministic Seismic Hazard Assessment

The deterministic procedure, developed by Costa et al [1] and subsequently widely applied [8, 9, 10, 11, 12, 13, 14, 15, 16] allows for a first-order seismic hazard mapping. Synthetic seismograms are constructed by the modal summation technique [17, 18, 19, 20] to model ground motion at the sites of interest, using the knowledge of the physical process of earthquake generation and wave propagation in realistic media. The procedure uses regional polygons to limit the area of validity of the proposed structural model, and parameters such as focal mechanism, seismogenic zones, earthquake catalogue to characterize the seismic source. The flowchart of the procedure is shown in Figure (1).

This deterministic apporach is completely different and complementary to the probabilistic approach as in general proposed (see e.g. Reiter [21] for an overview). It capably addresses aspects largely overlooked in the probabilistic approach such as (a) the effect of crustal properties on attenuation; (b) the derivation of ground motion parameters from synthetic time histories instead of using overly simplified attenuation functions; (c) the direct evaluation of resulting maps in terms of design parameters, and lowercase without requiring the adaptation of probabilistic maps to design ground motions; and (d) the generalization of design parameters to locations where there is little seismic history.

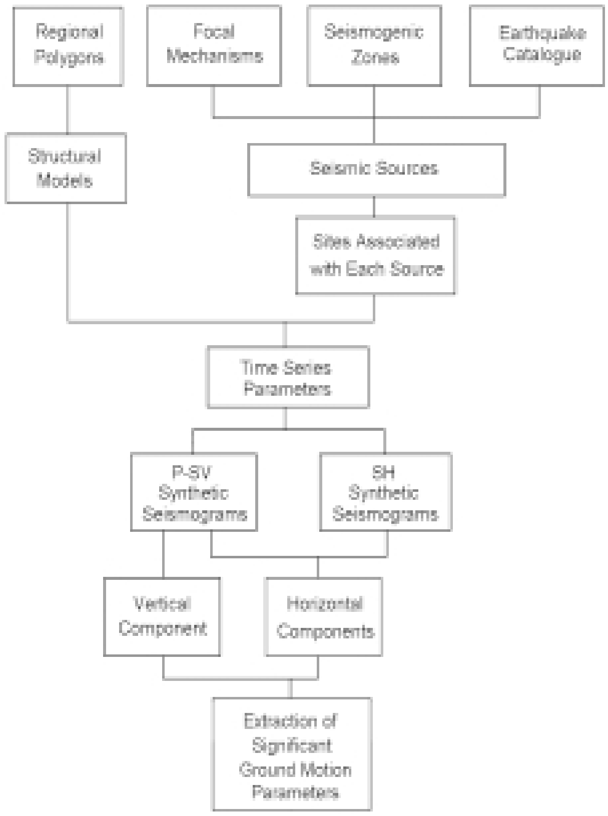


**Figure 1.** Flow chart scheme of the deterministic procedure (modified from Costa et al [1]). The vertical component is routinely not used.

The deterministic approach is also preferable in view of the limited seismological data availability and of the multiscale seismicity model formulated by Molchan et al [22]. According to this model only the ensemble of events that are geometrically small, compared with the elements of the seismotectonic regionalization, can be described by a log-linear frequency-magnitude (*FM*) relation. This condition, largely fulfilled by the early global investigation by Gutenberg and Richter (e.g. see Figure (49) of Bath [23]), has been subsequently violated in many investigations. This violation has given rise to the Characteristic Earthquake (*CE*) concept [24] in opposition to the Self-Organized criticality (*SOC*) paradigm [25]. The multiscale model implies that, in order to apply the probabilistic approach the seismic zonation must be made at several scales, depending upon the self-similarity conditions of the seismic events and the linearity of the log FM relation, in the magnitude range of interest.

## 3. Input Data

Indeed to compute synthetic seismograms, it is necessary to define the characteristics of the seismic sources and of the structural model representative of the studied area. The input data consist of an earthquake catalogue, of seismogenic zones with associated representative focal mechanisms, and of a structural model.

### 3.1. Earthquake Catalogue

One of the main advantages of the deterministic approach is that an earthquake catalogue complete for magnitude 5 and above is sufficient. Therefore it is much easier to collect the required information, compared to the probabilistic approach. The catalogue we used (catalogue *MORO*) is produced by Ramdani [26] for the period from 1900 to 1989, completed up to 1995 with the data collected by the seismic network of Morocco. For the region between $0^{o}$-$20^{o}W$ and $20^{o}$-$37^{o}N$ we have compared it with other catalogues: *NEIC* in the time period between 1910 and 1998, *ISC* for earthquakes between 1964 and 1994, and the catalogue by Benouar (*BEN*) up to 1990 [27, 28]. The region [$20^{o}$-$27^{o}N$] is not considered in this study since no significant event was ever recorded there.

Indeed the available catalogues show different locations for the same reported event. For the earthquakes with magnitude 5 and greater, listed in Table (1), the discrepancies reported by different sources show that the choice of the catalogue does not influence much the hazard results. In any case this choice is not critical since the smoothing procedure of the magnitude distribution, implemented in the deterministic approach [1], reduces the effects due to mislocation errors. We finally decided to use the *MORO* catalogue since it was earlier adopted by Tadili [6] and Jimenez et al [3] for seismic hazard assessment studies in Morocco. In such a way, we can better compare our deterministic results with the probabilistic ones already available.

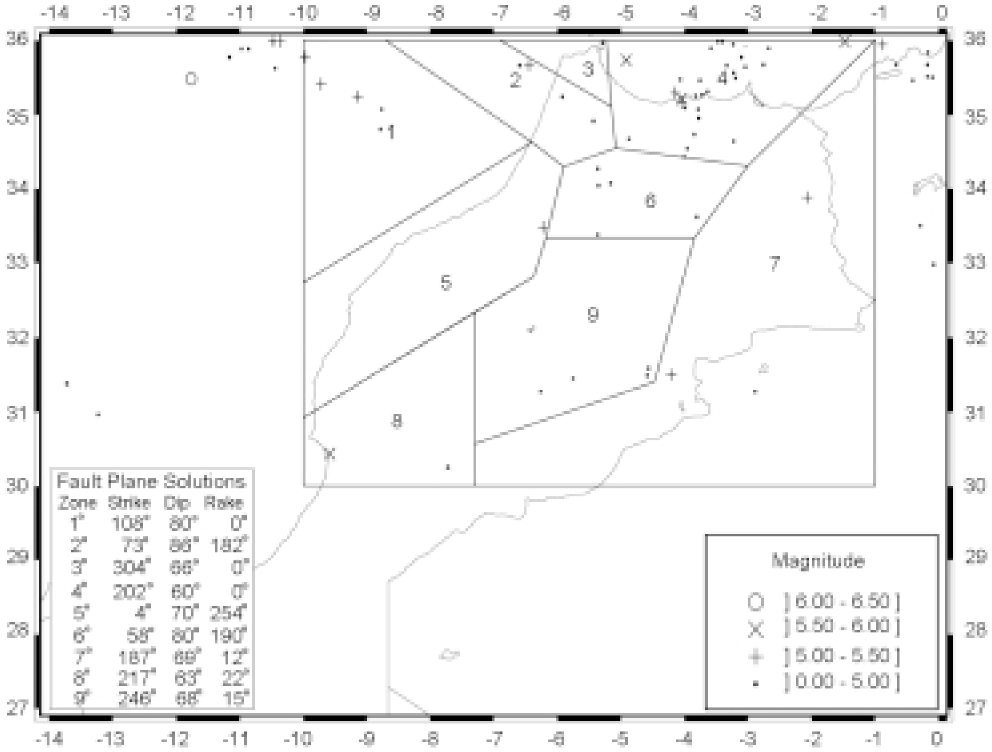
The *MORO* catalogue contains different estimates of the magnitude (magnitude computed from body waves, surface waves, and local magnitude). In order to be conservative in the computation of the synthetic seismograms we use the maximum among them. Given all the uncertainties in magnitude determination, we think that the best choice is to stay on the "safe" side.

**Table 1.** Comparison of the earthquake epicenters in the four catalogues.

| Date | Catalogue | Lat. | Long. | Mmax | H(km) |
|---|---|---|---|---|---|
| 1960/02/29 | MORO<br>NEIC<br>BEN | 30.45<br>30.00<br>30.45 | -9.61<br>-9.00<br>-9.62 | 6.0<br>6.3<br>6.2 | -<br>-<br>- |
| 1992/10/23 | MORO<br>NEIC<br>ISC | 31.51<br>31.35<br>31.29 | -4.23<br>-4.32<br>-4.33 | 5.2<br>5.3<br>5.2 | 22<br>28<br>5 |
| 1992/10/30 | MORO<br>NEIC<br>ISC | 31.5<br>31.28<br>31.25 | -4.61<br>-4.37<br>-4.38 | 5.0<br>5.2<br>5.1 | -<br>25<br>8 |
| 1994/05/26 | MORO<br>NEIC | 35.23<br>35.31 | -4.07<br>-4.10 | 5.9<br>6.0 | 10<br>9 |

### *3.2. Seismogenic Zones and Focal Mechanisms*

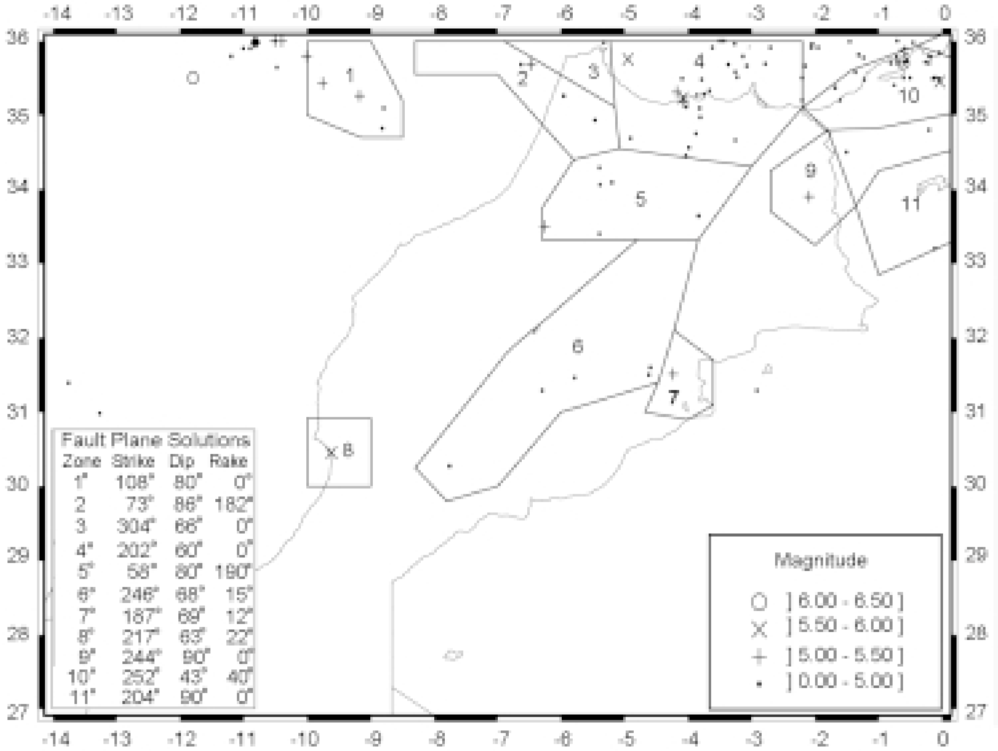
On the basis of the geologic, tectonic and seismicity evidences, Tadili [6] proposed a set of seismic zones for Morocco, shown in Figure (2). This zoning does not seem to satisfy the criteria defined in the deterministic approach, since the whole country is covered by the seismic zones, even if in some areas the seismicity is very low or absent. At first, we decided to run anyway the deterministic procedure using the original zones by Tadili [6]. Next, we defined a new set of seismogenic zones (Figure (3)), following the criteria generally adopted for



Fault Plane Solutions

| Zone | Strike | Dip | Rake |
|---|---|---|---|
| 1° | 108° | 80° | 0° |
| 2° | 73° | 86° | 182° |
| 3° | 304° | 66° | 0° |
| 4° | 202° | 60° | 0° |
| 5° | 4° | 70° | 254° |
| 6° | 58° | 80° | 190° |
| 7° | 187° | 69° | 12° |
| 8° | 217° | 63° | 22° |
| 9° | 246° | 68° | 15° |

**Figure 2.** Seismogenic zones defined by Tadili [6] (modified), used in variant 1, and associated fault plane solutions.



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| 5° | 58° | 80° | 190° |
| 6° | 246° | 68° | 15° |
| 7° | 187° | 69° | 12° |
| 8° | 217° | 63° | 22° |
| 9° | 244° | 90° | 0° |
| 10° | 252° | 43° | 40° |
| 11° | 204° | 90° | 0° |

**Figure 3.** Seismogenic zones used in variant 2, and associated fault plane solutions. The seismicity of the MORO catalogue is here integrated with the data from the Algerian catalogue used by Aoudia et al [11].

the deterministic approach. Therefore we reduced the spatial extension of the zones taking into account the seismicity of Morocco, and we carefully arranged the zones at the border with Algeria, considering the work by Aoudia et al [11].

For the definition of the focal mechanism associated with each seismogenic zone, we have collected the published fault plane solutions for the territory of Morocco. The fault plane solutions used are derived from Tadili and Ramdani [29], Medina and Cherkaoui [30], Bufom et al [31], ElAlami et al [5], Geo-Ter [32], and *CMT* (Centroid Moment Tensor) determinations for the region. In the zones where no focal-plane solution is available, the solution available in the nearest zone is considered, provided that it is compatible with the seismotectonic regime. The values of strike, dip and rake for the representative focal mechanism of each seismogenic zone are given in Figures (2) and (3).

### *3.3. Structural Model*

A flat layered anelastic structural model must be defined in order to run the procedure. Layers are described by their thickness, density, P- and S-wave velocity, and attenuation. The velocity model we used is derived from the one computed by Cherkaoui [2]. We modified the uppermost 2.5*km* of the model, considering a layer with $V_s = 1.9 km/s$ to account for the sedimentary cover. The model does not differ notably from the one adopted by Aoudia et al [11] for Algeria. The parameters of the layers (thickness, density, P- and S- wave velocity and attenuation) are given in Table (2).

## 4. Computations

We compute seismic hazard for two variants: in variant 1 we adopt the original seismogenic zones defined by Tadili [6] and the earthquake catalogue *MORO*, while in variant 2 we use the new seismogenic zones defined in Section 3.2, and integrate the *MORO* catalogue to the East with the Algerian data used by Aoudia et al [11].

In order to account for mislocations and uncertainties present in the earthquake catalogue, and to consider fault dimensions, the distribution of the maximum observed magnitude over Morocco is discretized and smoothed. First, the studied region is divided into cells of 0.2°x0.2° and the maximum observed magnitudes of the earthquakes which occurred within each cell is determined. A smoothing window is then applied (with radius of three cells), so that earthquake magnitudes are reported not only in the central cell, but also in the neighboring ones, if they fall within a seismogenic zone [1]. The maps shown in Figures (4) and (5) are the results of the application of this method to the two set of seismogenic zones, used in variant 1 and variant 2 respectively. Each seismic source is represented by a double-couple point source located in the center of each cell. The orientation of the double-couple point source is fixed accordingly to the fault-plane solutions representative of the seismogenic zone containing the source.

**Table 2.** Velocity model used for the computation of synthetic seismograms.

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Once the structural models and the source characteristics are defined, sites are considered on a grid 0.2° x 0.2° covering the whole territory, and synthetic seismograms are computed by the modal summation technique [17, 18, 19, 20]. To reduce the number of computed seismograms, the source receiver distance is kept below an upper threshold, which is considered to be a function of the magnitude associated with the source. The maximum source-receiver distance is set to 25, 50, and 90*km* for $M$<6, 6<$M$<7 and $M$ 7, respectively. At each receiver the *P-SV* (radial component) and *SH* (transverse component) are computed for a seismic moment of $1\text{x}10^{-7}$*Nm*. The amplitudes are then properly scaled according to the smoothed magnitude associated with the cell of the source using the moment-magnitude relation by Kanamori [33] and the spectral scaling law proposed by Gusev [34] as reported in Aki [35]. The horizontal components are first rotated to a common reference system (*NS*- and *EW*-directions) and then their vector sum is calculated. From these seismograms, at each point of the 0.2 grid we select the maximum values of acceleration (*AMAX*), velocity (*VMAX*) and displacement (*DMAX*). The synthetic signals are computed for an upper frequency content of 1Hz, and the scaled point-source approximation [34] is still acceptable. It has been shown by Panza et al [36] that for displacements and for velocities 1*Hz* cutoff does not lead to significant losses in the peak amplitudes. For accelerations, the deterministic results may be extended to frequencies higher than 1*Hz* by using design response spectra to obtain the Design Ground Acceleration (*DGA*). For this purpose we have adopted the Eurocode 8 (*EC8* [37]), which defines the normalized elastic acceleration response spectrum of the ground motion, for 5% critical damping. This choice is not obliged, and other design spectra can be used if more appropriate for the studied area.

## 5. Discussion of Results and Conclusion

Figure (6) shows the maximum ground motion computed

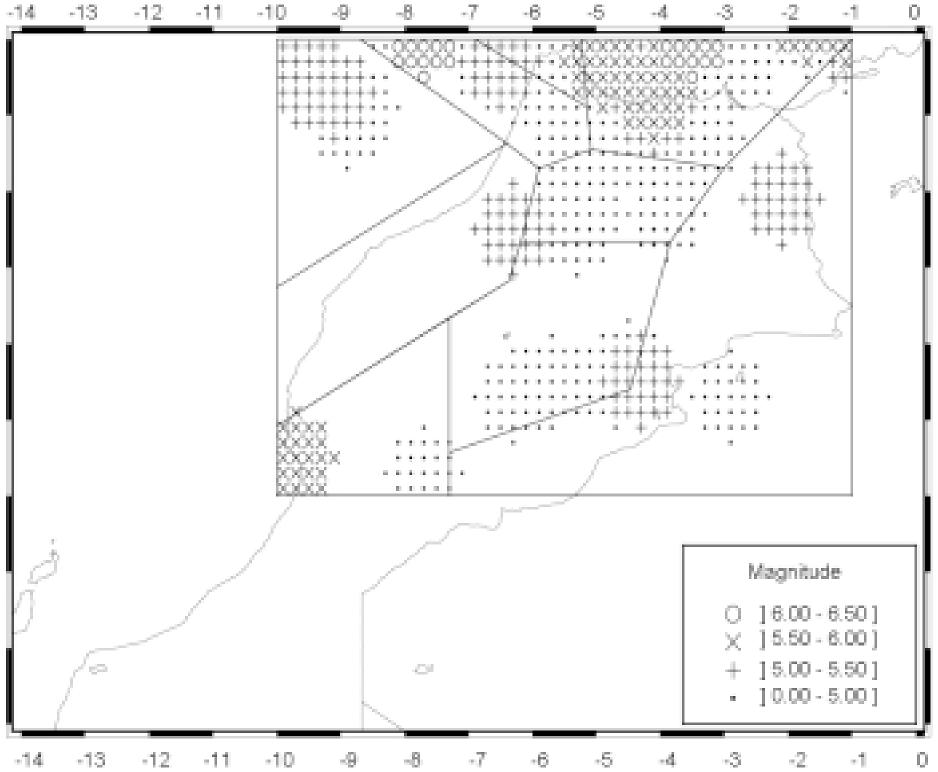

**Figure 4.** Smoothed magnitude distribution within the seismogenic zones defined by Tadili [6], used in variant 1.

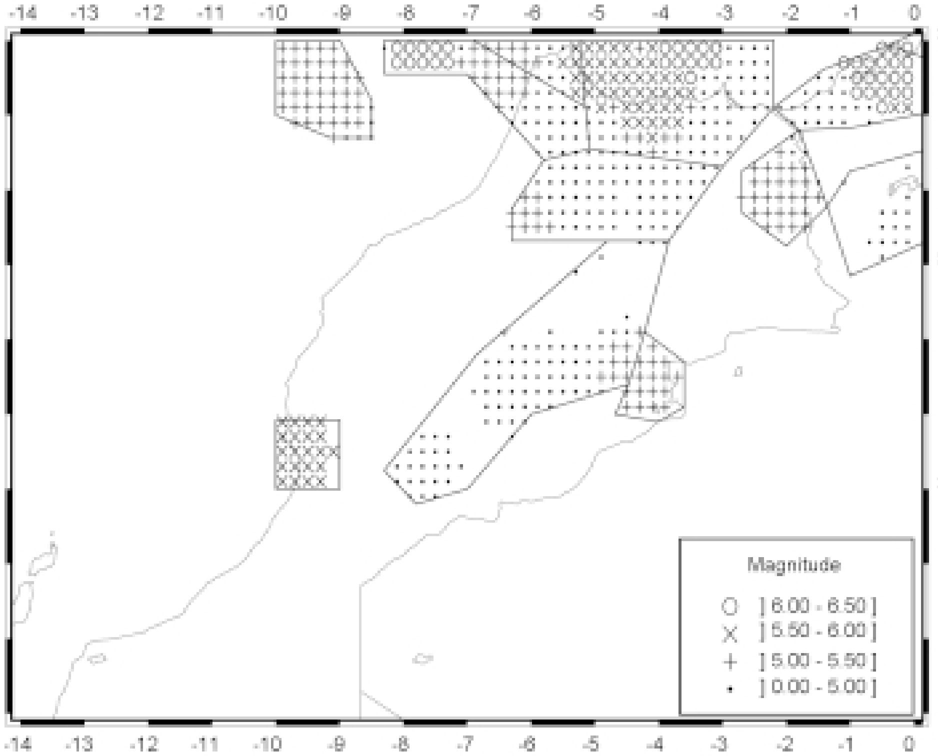

**Figure 5.** Smoothed magnitude distribution within the seismogenic zones defined in this paper, used in variant 2.

in variant 1, adopting the original seismogenic zones proposed by Tadili [6]. The maximal values are obtained in the region within the latitudes 30°-31.5°*N* and longitudes 9°-10°*W* where the largest ever recorded event in Morocco, the 1960 Agadir earthquake with magnitude 6.0, is located [38]. Relevant ground shaking is also obtained at latitudes larger than 34°*N*. This was expected, since northeast Morocco is one of the most seismically active regions in the country. Strong earthquakes have occurred in the past and some of them caused many

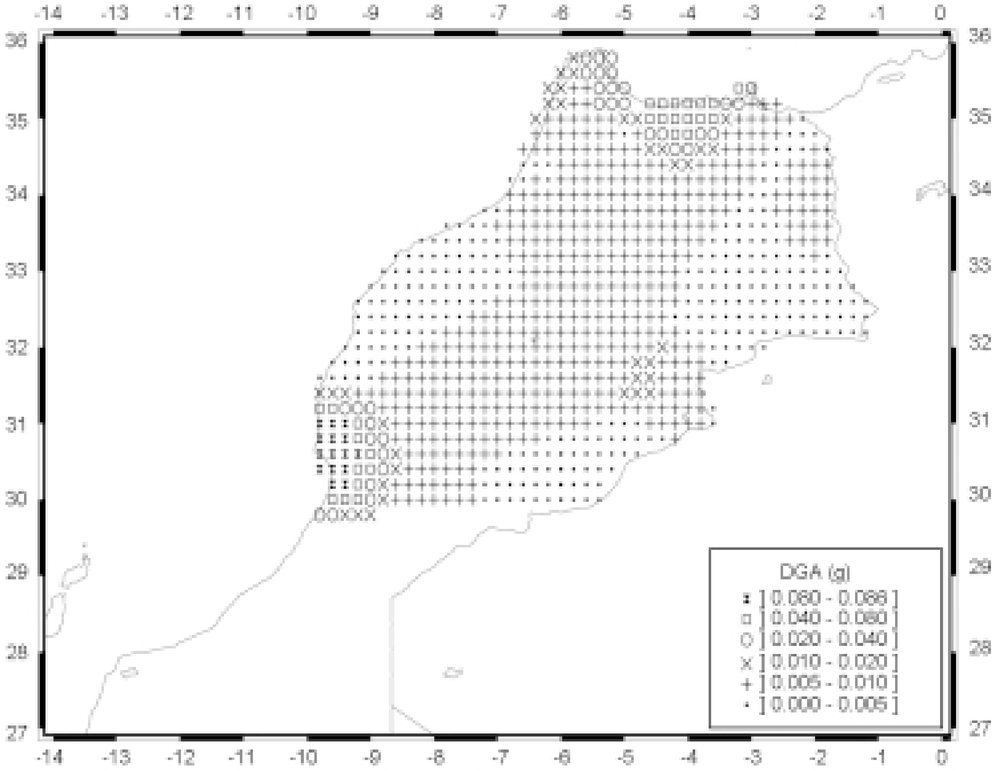

**Figure 6a.** Design ground acceleration obtained in variant 1.

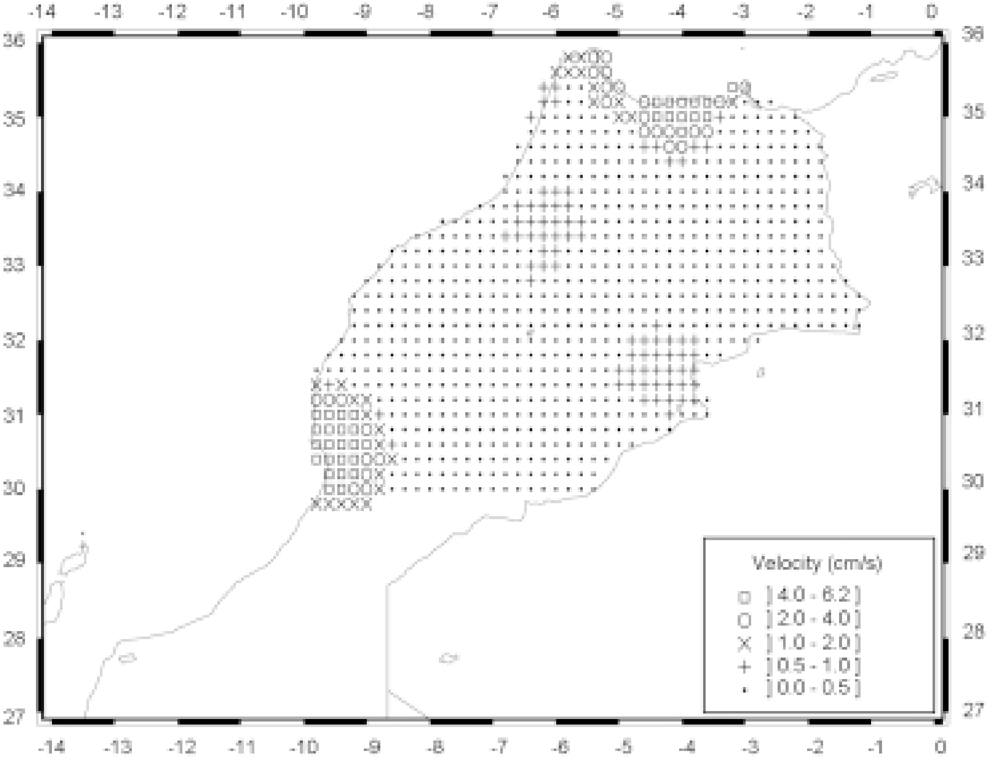

**Figure 6b.** Peak velocities obtained in variant 1.

casualties and much destruction over a large area. Among them is the earthquake of 26 May 1994 of magnitude 5.9. In the other parts of Morocco the modeling leads to very low peak values, with accelerations below 0.01*g*.

Figures (7a), (7b) and (7c) show the second variant of seismic hazard maps, based on the new definition of seismogenic zones given in Section 3.2. In comparison with variant 1, due to the reduced spatial distribution of sources, see Figure (5), the computations are simply not carried out where the expected hazard was not relevant in

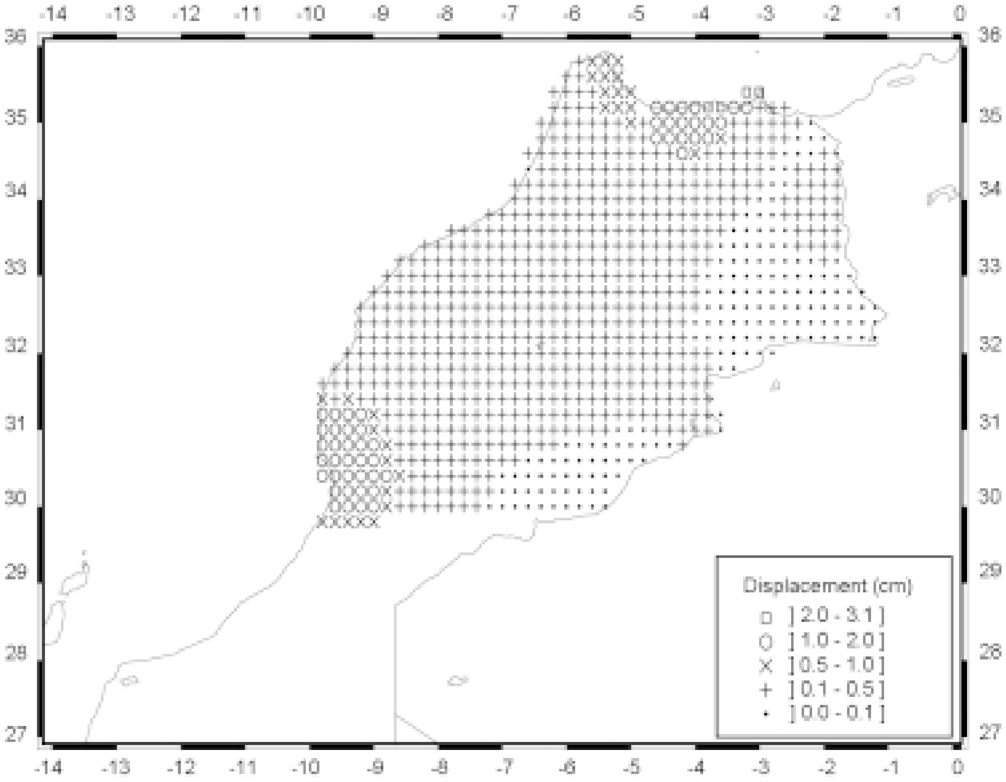

**Figure 6c.** Peak displacements obtained in variant 1.

variant 1. Still the regions where the highest ground motion is expected are identified: Al Hoceima region in north Morocco and Agadir region in the southwest of the country.

The estimation of the *DGA*, *VMAX*, *DMAX* obtained in this study takes into account the Moroccan and Atlantic seismicity (up to 100*km* off the coasts of Morocco), and the seismic zones defined for Algeria by Aoudia et al [11]. We have also analyzed in the earthquake catalogues the seismicity of southern Spain and of the Mediterranean Sea, 100*km* off the coasts of Morocco. Since the magnitude of the strongest events reported for those regions is not larger than the magnitude shown in Figures (4) and (5) for northern Morocco, the results of the deterministic approach would not change adding some seismogenic zones at a latitude larger than 36°*N*.

The question arises whether a very large event like the Nov. 1, 1755 earthquake (the well known "Lisbon earthquake") occurring offshore the Portuguese coasts, could increase the hazard level in Morocco. In a comprehensive study of the Lisbon earthquake, Johnston [39] shows a generalized intensity map where a spot of grade *VIII* is located along the North-Western lowercase of Morocco. A modeling of the ground motion due to a $M=8.4$ event occurring at the epicentral location proposed by Machado [40], 11.25°*W*-36.45°*N*, has been performed. The ground shaking values obtained do not perturb significantly the results obtained through the standard application of the deterministic procedure shown in Figures (6) and (7). For the Lisbon event, the *DGA* computed in Northern Morocco is around 0.03-0.04*g*, and decreases smoothly down to 0.01*g* in the Agadir region. Velocities vary between 4*cm/s* and 1*cm/s* from North to South, while peak displacements around 3*cm* are obtained all along the coast, but for periods of about 30*s*. Therefore we might expect some damage mostly for those structures characterized by very large periods of resonance. A typical example is the Hassan Tower, a square tower in Rabat City, with side 16*m*. There are reports saying that the tower was in origin 80*m* tall, and its upper half collapsed due to the 1755 earthquake, but others claim that the Hassan Tower was never built to completion (for a detailed discussion, see Elmrabet et al [41]). Johnston [39] points out that for the Lisbon earthquake there is not a breakdown made as to deaths and damages due to strong shaking, tsunami and fire; but according to Martinez Solares et al [42], it looks like for the coastal region the highest risk for the population was by far associated with the tsunami wave, and this is also confirmed by Elmrabet et al [41]. Tsunami estimation is beyond the purpose of this work, but we believe that a dedicated modeling of the tsunami generated by events similar to the Lisbon earthquake could contribute to a more comprehensive understanding of the hazard in the region.

The *DGA* values of Figures (6a) and (7a) have been compared with the probabilistic estimations made by Jimenez et al [3] as shown in Figure (8). The largest accelerations obtained with the two approaches are very similar (0.09 and 0.10$g$ for deterministic and probabilistic respectively), but some discrepancies exist in the location of the areas characterized by the highest hazard. The most relevant ones are the Agadir region, that is very well pointed out by the deterministic approach and is not so outstanding in the probabilistic map, and the High Atlas region that is characterized by $PGA$ values of 0.08$g$ in the probabilistic approach, and is not evident in the deterministic maps. Such differences can be very likely explained looking at the fundamentals of the two approaches. As a general idea,

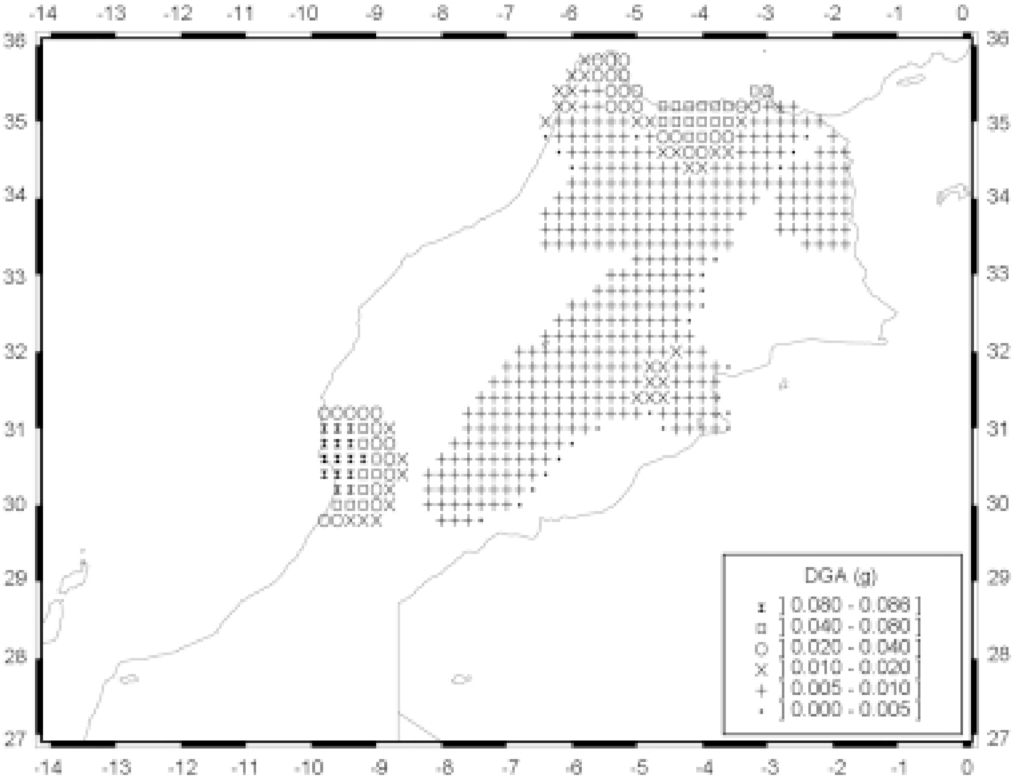

**Figure 7a.** Design ground acceleration obtained in variant 2.

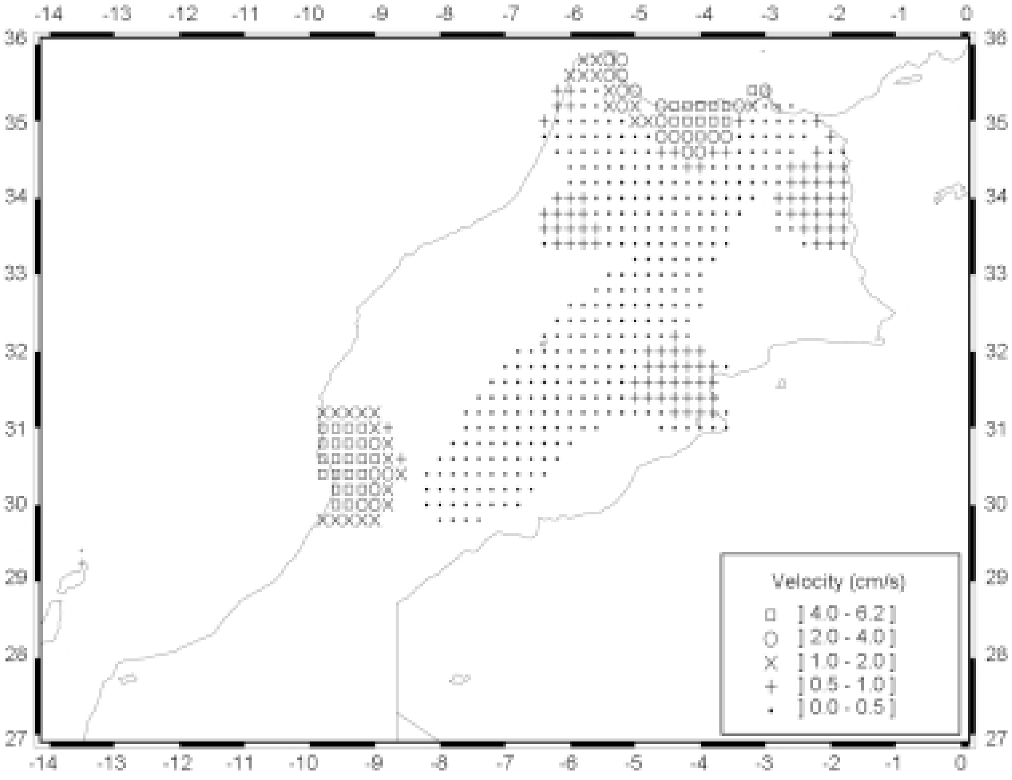

**Figure 7b.** Peak velocities obtained in variant 2.

in the probabilistic approach the seismicity level in each seismogenic zone is obtained as a weighted sum of the contributions due to recorded earthquakes grouped in magnitude classes. On the contrary, with the deterministic approach we are mainly interested in the spatial distribution of the largest events recorded, with no interest in their temporal distribution. In case of a high annual occurrence rate of events with magnitude smaller than the maximum observed one, the probabilistic approach will often overestimate the hazard, compared to the deterministic

**Figure 7c.** Peak displacements obtained in variant 2.

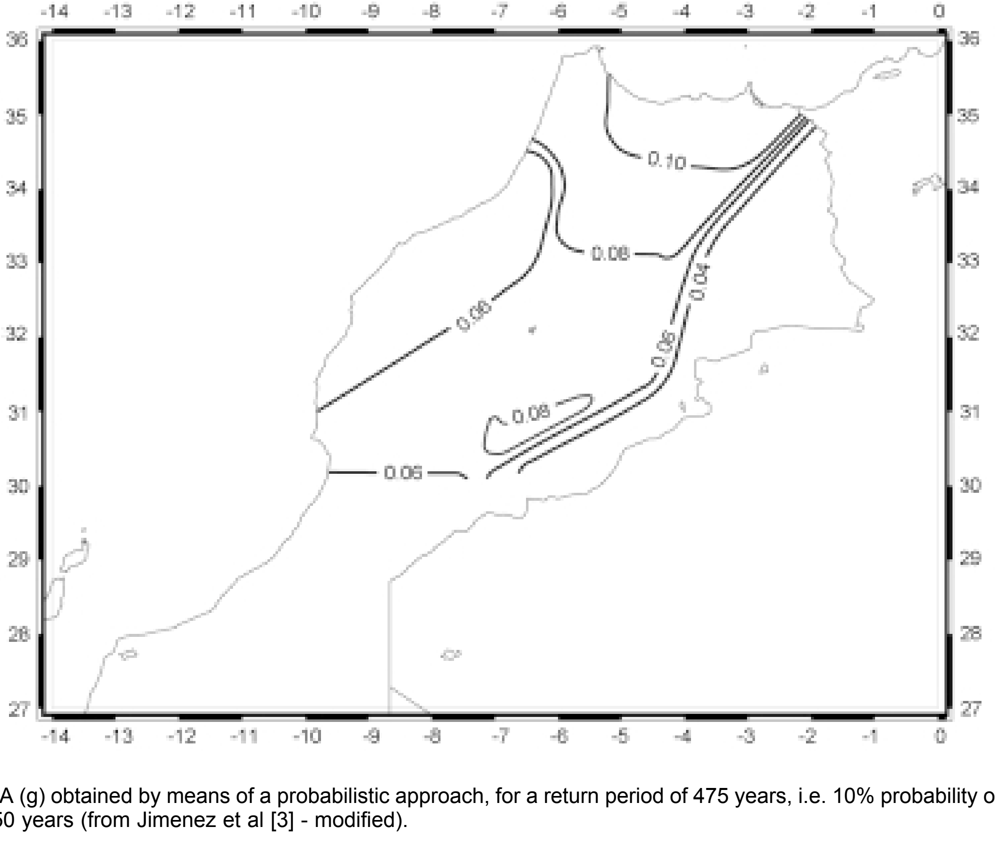

**Figure 8.** PGA (g) obtained by means of a probabilistic approach, for a return period of 475 years, i.e. 10% probability of exceedance in 50 years (from Jimenez et al [3] - modified).

approach. This may be the explanation for the different results obtained in the High Atlas region. The opposite happens when the annual occurrence rate for small events is low: probabilistic results will underestimate the hazard compared to the deterministic results, like what happens in the Agadir region. The role played by lack of information in the seismic history is evident. Whenever the information about the background seismicity is missing because of catalogue incompleteness at low magnitudes, there will be very likely a wrong hazard underestimation in the probabilistic results. On the other hand, to mistakenly underestimate the hazard with the deterministic approach, there must be lack of information about the largest events in the area, which is a situation more unlikely to occur. So, for the deterministic approach catalogue completeness is requested only for relatively strong events ($M > 5$), while probabilistic seismic hazard analyses are particularly sensitive to the catalogue completeness, difficult to achieve in the mid-low magnitude range for historical events. New preliminary results from *IGCP*-382 project SESAME [43], obtained using part of the seismogenic zones of Figure (3), show a better agreement with the deterministic results of Figure (7a), although absolute *PGA* values are higher due, most probably, to the attenuation law used (Garcia-Fernandez, personal communication).

The first-order zoning we carried out must be considered as a good starting point for more detailed analyses, to be performed wherever more information about seismic sources and local site conditions, are or become available. Even though the method we have followed is deterministic, it is suitable to be used in new integrated procedures which combine probabilistic and deterministic approaches, minimizing their respective drawbacks. In fact, as pointed out very clearly by Reiter [21], the deterministic approach would be perfect if our knowledge of earthquakes and earthquake ground motion were complete enough to allow good approximation of when, where and how big future earthquakes will be, and which level of shaking they would generate. On the other hand, a probabilistic approach would be the best if our scientific knowledge was limited but we had a good understanding of the uncertainties so that we could overcome the lack of information. Unfortunately, neither situation is true. An example of integrated procedure where the deterministic part is based on the computations of synthetic seismograms can be found in Orozova and Suhadolc [44].

The outcome of the deterministic procedure can be particularly helpful for the design or reinforcement of special buildings, as seismic hazard maps are based on the computation of synthetic time histories that remain available at the end of the procedure. In addition to considering peak displacement, velocity and acceleration, more sophisticated analyses can be carried out by civil engineers, like the estimation of the Earthquake Input Energy (*EI*), a measure that correlates well with real damage to buildings, as pointed out by Uang and Bertero [45]. This is especially meaningful for those areas where no instrumental recording of damaging earthquakes exists.

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