Seismic hazard assessment for Jordan and neighbouring areas

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ABSTRACT Seismic hazard in Jordan and neighbouring areas was assessed following the standard probabilistic approach. Eighteen seismic sources have been identified and characterized using appropriate seismic parameters. Two ground motion models, were used and their results were compared to explore the hazard sensitivity. The hazard results are given in the form of maps of *PGA* and *SA* (at 0.1, 0.2, 0.3, 0.5, 1.0 and 2.0 s), for a 10% probability of exceedance in 50 years for rock sites. Maximum *PGA* values within Jordanian territory range between 0.25 and 0.30 g. Maximum *SA* values at 0.2 s and 1.0 s range between 0.6-0.7 g and 0.15-0.20 g, respectively. A comparison of *PGA* values for two cities in Jordan (Amman and Aqaba) shows that the influence of the ground motion model is negligible for the probability levels of engineering interest. Results of the seismic hazard analysis were used to develop a new macrozonation map for Jordan as well as an associated suite of elastic response spectra applicable for the different seismic zones. In this map, Jordan is divided into three seismic zones with values of the seismic zone factor ranging between 0.06 and 0.15.

1. Introduction

Jordan is situated east of the central part of the main tectonic feature in the Levant i.e. the Dead Sea Fault (DSF) system (or Dead Sea transform fault) which constitutes the plate boundary between the Arabian and the African plates. The DSF runs for about 1000 km from the Gulf of Aqaba in the south to the East Anatolian fault in the north. The motion is left lateral strike slip (e.g. Garfunkel *et al.*, 1981) with several depressions corresponding to pull-apart basins (e.g. the Dead Sea pull-apart) developing at jogs between successive segments of the fault (e.g. Klinger *et al.*, 1999). The basins along the Dead Sea Rift are asymmetrical with steeper bounding faults on the eastern margin. To the north, as the fault system enters Syria and Lebanon the relative simplicity of the fault system changes into a much more complex system with several branching off structures (see inset in Fig. 1).

The slip rate of the DSF zone remains poorly constrained although geological observations and plate tectonic models suggest that it accommodates the motion at a major plate tectonic feature i.e. the boundary between Africa and Arabia. The estimated slip rates obtained from geological analysis or from plate tectonics analysis vary between 10 and 1 mm yr^{-1} (e.g. Klinger *et al.*, 2000 and references therein). The DSF system has produced large earthquakes ($M_S \geq 7$) in the past with strong damaging effects in Jordan although it has been relatively quiet in the last century (e.g. Ambraseys and Barazangi, 1989; Ambraseys and Jackson, 1998; Ambraseys, 2001).

The first attempts to map seismic hazard for the Levant region and for Jordan were performed in the 1980s (Ben Menahem, 1981; Shapira, 1981; Yücemen, 1985; Arieh and Rabinowitz, 1989). During the 1990s a number of studies obtained seismic hazard estimates for Jordan and its neighbouring region, for the country at a national scale and also for specific sites within Jordan (e.g. Yücemen, 1992, 1995; Batayneh, 1994; Al-Tarazi, 1994, 1999; Husein Malkawi *et al*., 1995; Al-Homoud and Husein Malkawi, 1995; Fahmi *et al.*, 1996). Among them, the study of Yücemen (1992) assessed seismic hazard in Jordan and its vicinity through the use of probabilistic and statistical methods and the results were given in the form of iso-intensity maps and iso-acceleration maps using the Esteva and Villaverde (1973) attenuation relation. The problems associated with the delineation of seismic source zones were further addressed and discussed in the model by Yücemen (1995) which was applied for sensitivity analysis to three different cities in Jordan. Al-Tarazi (1999) gives probabilistic seismic hazard estimates for the eastern Mediterranean and Sinai region through the use of Esteva´s (1974) attenuation relation and based on the earthquake catalogue and the seismic line-source model in the former work by Al-Tarazi (1994), where different models for seismic sources and for the estimation of seismic parameters were applied and the results compared. In both studies, the results are given in the form of iso-acceleration maps for different return periods (90% probability of not being exceeded in 50, 100 and 200 years). Seismic hazard estimates for dam sites in Jordan were given in Al-Homoud and Husein Malkawi (1995) based on a fault source model using Esteva's (1974) attenuation relation and considering values of peak ground acceleration (*PGA*) for different exposure times and different probabilities of not being exceeded.

More recently, probabilistic hazard assessments for Jordan, in terms of *PGA* and spectral acceleration (*SA*) at 0.2 s through the use of Ambraseys *et al*. (1996) attenuation relation, were presented by Yücemen *et al*. (2005). In this work, exponential magnitude distribution and characteristic earthquake models were considered and the hazard results for four cities in Jordan estimated through the different assumptions were compared.

Seismic hazard assessments for the eastern Mediterranean and the Levant region were also performed in the context of international initiatives and programmes, and based on regional approaches (e.g. Giardini, 1999; Jiménez *et al*., 2003; Jiménez 2006).

The first seismic regulations in the Jordanian building codes were included in the Jordan Code for Loads and Forces (Jordanian National Building Council, 1985). The computations for the equivalent static forces were based on an intensity factor that was quantified for four different zones based on an intensity map using the Mercalli scale. In 2005, the first Jordanian Code for Earthquake-Resistant Buildings (Jordanian National Building Council, 2005) was issued and the design earthquake loading was based on a macrozonation map that divided the Jordanian territory into four seismic zones, namely 1, 2A, 2B and 3 with Z values of 0.075, 0.15, 0.2 and 0.3, respectively. The zonation map in the code was derived from the results of several studies concerned with the assessment of seismic hazard in Jordan and neighbouring areas (Building Research Center, 2004).

The aim of the present study is to propose new probabilistic seismic hazard estimates for the Jordanian territory and neighbouring region using Cornell's (1968) standard probabilistic approach, and a new macrozonation map in connection with the revision and updating of the Jordanian national building codes. The results of the mapping quantify seismic hazard in terms of *PGA* and *SA* (at 0.1, 0.2, 0.3, 0.5, 1.0 and 2.0 s) for a probability of exceedence of 10% in 50 years for rock sites. Based on these results, a new macrozonation map is proposed for Jordan with an associated set of design response spectra applicable to different seismic zones. Full details on the seismic hazard assessment and mapping of Jordan can be found in Jiménez (2004) and Jiménez *et al.* (2005).

2. Probabilistic seimic hazard methodology

The probabilistic seismic hazard assessment in this study follows the methodology originally proposed by Cornell (1968). This approach is implemented in a number of computer codes, e.g. EQRISK (McGuire, 1976), SEISRISK III (Bender and Perkins, 1987) and FRISK88M (Risk Engineering Inc., 1996).

Cornell´s method is based on Poisson´s distribution of the earthquake process and requires:

- identification of the seismic source zones where the region for which the hazard is to be computed is subdivided according to tectonic, geophysical, geological and seismological data;
- establishment of the magnitude-frequency parameters (*b*-value and activity rate) according to the Gutenberg-Richter law and estimation of the maximum magnitude (M_{max}) value;
- computation of hazard through the use of an adequate attenuation relationship for the region under investigation.

To compute the seismic hazard in this work the code SEISRISK III (Bender and Perkins, 1987) has been used. The input for the SEISRISK III code requires the attenuation relationship in tabular form (ground motion versus magnitude and distance) and the description of each source, including geometry, uncertainty in earthquake location and occurrence rates (number of earthquake occurrences at given magnitude intervals normalized to a given number of years). The earthquake location uncertainty can be incorporated by considering locations normally distributed around their mean locations with standard deviations Φ, which is equivalent to considering source-zone location uncertainty, e.g. soft boundaries. The two basic types of seismic sources, line sources and area sources, considered in the Cornell methodology are standard options in SEISRISK III. The definitions of these two types of sources are, in general, somewhat arbitrary and are not completely realistic. For example, the distribution of epicentres in the Dead Sea certainly is not consistent with the assumption of a line source although this approximation exaggerating reality might be a valid and useful technique for specific applications. In this study, all seismic sources have been modelled as area source-zones rather than line sources, even where the fault zone is well defined, both geologically and seismologically. This is due to the finite width of fault zones (e.g. Dead Sea rift), their inclinations and the inherent hypocenter uncertainty. Soft boundaries of variable width have been considered for all area sources. Following the Bender and Perkins (1987) formulation, hazard is computed at each point of the study area through discrete summation of the individual contributions from the mass center of the concentric circular sectors into which the source zones are subdivided. Finally, ground motion variability is incorporated in the computations by assuming a lognormal distribution of the ground-motion parameter with standard deviation Φ in log acceleration.

2.1. Seismicity and earthquake catalogue

Historical seismicity shows that large earthquakes ($M \geq 7$) occur in the region of the DSF system (e.g. Ambraseys and Barazangi, 1989; Ambraseys and Jackson, 1998) although it has been relatively quiet in the last century (Ambraseys, 2001). In Jordan and its vicinity, some of the largest damaging earthquakes of the last 200 years are the 1995 M_w 7.2 earthquake in the Gulf of Aqaba in the south (Klinger *et al*., 1999, Al-Tarazi, 2000; Hofstetter *et al*., 2003), the 1927 M_S 6.1 earthquake occurring at the northern tip of the Dead Sea (Ben Menahem *et al*., 1976; Shapira *et al*., 1993), and the 1837 M_S 7.1 earthquake in Lebanon, in the north (Ambraseys, 1997; Ambraseys and Jackson, 1998).

The earthquake catalogue used in this study was specifically compiled by Al-Tarazi (1992) to cover Jordan and surrounding regions and spans from 1 AD to 1999 AD. This earthquake list is based on the integration of existing catalogues, cross-checking for redundancy, quality and authenticity of data sources, and for homogeneous reporting of the basic parameters. The individual sources of information contributing to the catalogue are referred to in detail in the original work by Al-Tarazi (1992) and reported in Building Research Center (2004). The earthquake catalogue for Jordan and surrounding regions is divided into two main parts covering the historical (1-1899 AD) and the instrumental (1900-1999) periods. The historical part contains 52 major earthquakes that struck the area over the period 1-1899 A.D., whereas the second part of the catalogue contains a much larger number of more recent earthquakes spanning over the period 1900-1999 A.D.

As seen in Fig. 1, the seismic activity concentrates mainly along the DSF system, showing the most important and most active tectonic structure in the region. In its southern segment, the distribution of epicentres strikes essentially in a more or less N-S direction from the Gulf of Aqaba (at around 29.5º N) to the Sea of Galilee (at around 33º N). As the system enters southern Lebanon (north, around 33º N), the seismicity is more distributed, spreading over a wider region reflecting to the activity of the faults (e.g. Roum, Serghaya) that branch from the main transform fault. To the north, epicentres reflect the activity of the Yammouneh fault as the main northward continuation of the DSF system.

The largest earthquakes associated with the DSF system have reported magnitudes in the range of 6.5-7.5. In the past 2000 years, more intense historical activity within the 500 km fault segment, north of the Dead Sea, is reported (with a minimum of 10 such large earthquakes having occurred) as compared to the segment between the Dead Sea and the Gulf of Aqaba where only a few large events are reported during the same period [see Klinger *et al*. (2000) and references therein]. During the instrumental period most events have moderate magnitudes (less than 4.5) although not all stronger earthquakes occur on the main DSF structure (e.g. the 1984 M_w 5.3 occurring west of the Sea of Galilee).

2.2. Seismic source zones for hazard assessment

The basis of the seismogenic zonation is the source model developed in the studies for the updating of the national building code (Building Research Center, 2004; Jiménez, 2004). Based on the geology, the local and regional tectonics of the country, historical and instrumental seismic data, and microearthquake surveys, 14 seismic source zones were initially defined (Building

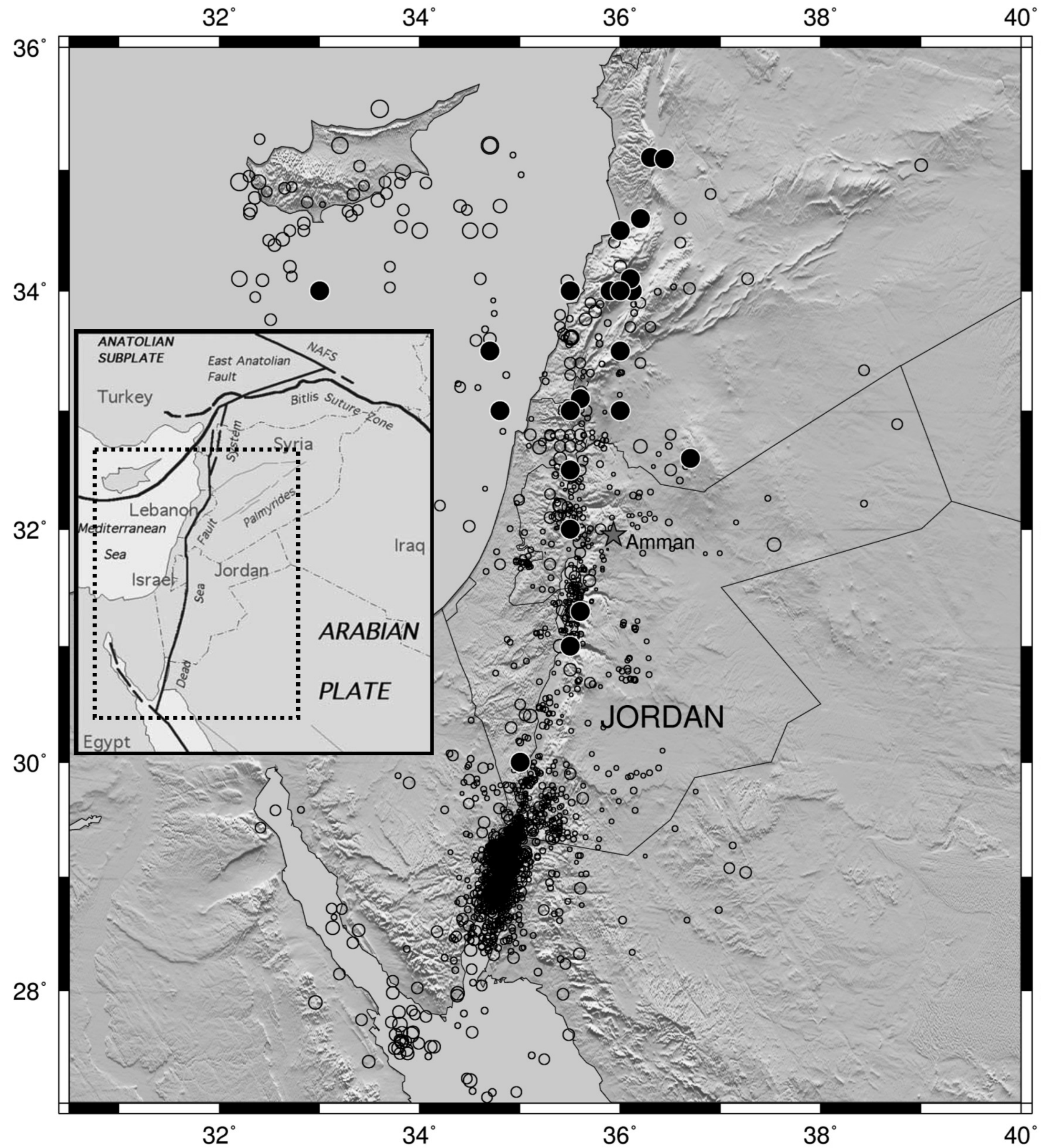

Fig. 1 - Seismicity in Jordan and neighbouring region. Solid circles indicate historical events (pre-1900), open circles correspond to events in the 20th century. Inset: major regional tectonic features in the Levant region [modified from Brew (2001) in Guidoboni *et al*. (2004)].

Research Center, 2004) as area sources, enclosed by latitudes 27.0°N and 35.5°N and longitudes 32.0°E and 39.0°E. These sources were redesigned and upgraded at a later stage to 18 area source zones (SZ) as detailed in Table 1 and described in the following paragraphs. Fig. 2 depicts the source zone model and the regional seismicity above magnitude M_L 4.0 as given by the Jordanian seismic catalogue.

SZs 1 and 2 represent the two main segments of the DSF system to the west of the country

Table 1 - Seismogenic source zones and associated seismic parameters: *b*-value (*b*-constant of Gutenberg-Richter relationship, M_{max} (upper bound magnitude), λ_4 (annual rate of $M \geq 4.0$ earthquakes).

N°	Source	*b*-value	M_{max}	λ_4
1	Dead Sea-Jordan River	0.75	7.5	0.330
2	Wadi Araba	0.82	6.6	0.110
3	Yammouneh-Roum	0.92	8.0	1.470
4	Palmira	0.96	6.0	0.120
5	Gulf of Aqaba	0.85	6.5	1.510
6	Gulf of Suez-South	1.07	7.0	0.540
7	Gulf of Suez-North	0.80	7.0	0.190
8	Sirhan Faults	0.71	7.0	0.050
9	Fara' Haifa	0.86	5.8	0.090
10	SE Mediterranean 1	0.80	5.8	1.750
11	SE Mediterranean 2	1.05	5.8	0.490
12	SE Mediterranean 3	0.92	7.5	0.090
13	Cyprus	0.98	8.0	2.740
14	Wadi Karak	0.44	4.7	0.023
15	SE Maan	0.29	4.6	0.029
16	East of Gulf of Aqaba	0.40	5.9	0.054
17	Central Sinai	0.30	4.0	0.010
18	North East Gaza	0.34	4.5	0.022

posing the highest seismic threat in Jordan with the southern segment being less active than the northern one. SZs 3 and 4 correspond to the northward continuation of the DSF system incorporating the faults branching from the main system and the Yammouneh fault. SZs 5, 6 and 7 include the activity of the Red Sea system in the Gulf of Aqaba and the Gulf of Suez, respectively. SZs 8 and 9 are located to the NE and NW of Jordan, corresponding to moderate seismic activity at present although within SZ 8 three destructive earthquakes are reported to have occurred in the past. The 1984 earthquake with magnitude above 5 is reported within SZ 9. SZs 10, 11, 12 and 13 represent three active sources of seismicity in the Mediterranean Sea and seismicity in Cyprus, respectively. SZs 14, 15 and 16 correspond to locations of major faults in central and southern Jordan with activity of small earthquakes but no reports on historical earthquakes. SZs 17 and 18 correspond to low seismicity areas and are delineated mainly on the basis of geology.

Seismic parameters of source zones within Jordan (SZs 1, 2, 5, 8, 9, 14, 15, 16, 17, and 18) namely the *b*-constant of the Gutenberg-Richter relationship (Gutenberg and Richter, 1956), the upper bound magnitude M_{max} and the annual rate of seismic activity for $M \geq 4.0$, λ_4, were determined using the Kijko and Sellevol (1989, 1992) approach. Seismic parameters and geometries of sources in the Mediterranean Sea and in neighboring countries (SZs 3, 4, 6, 7, 10, 11, 12 and 13) for which the Jordanian earthquake catalogue has a less dense coverage have been adopted from published literature on hazard projects in the region (Jiménez *et al.*, 2001, 2003;

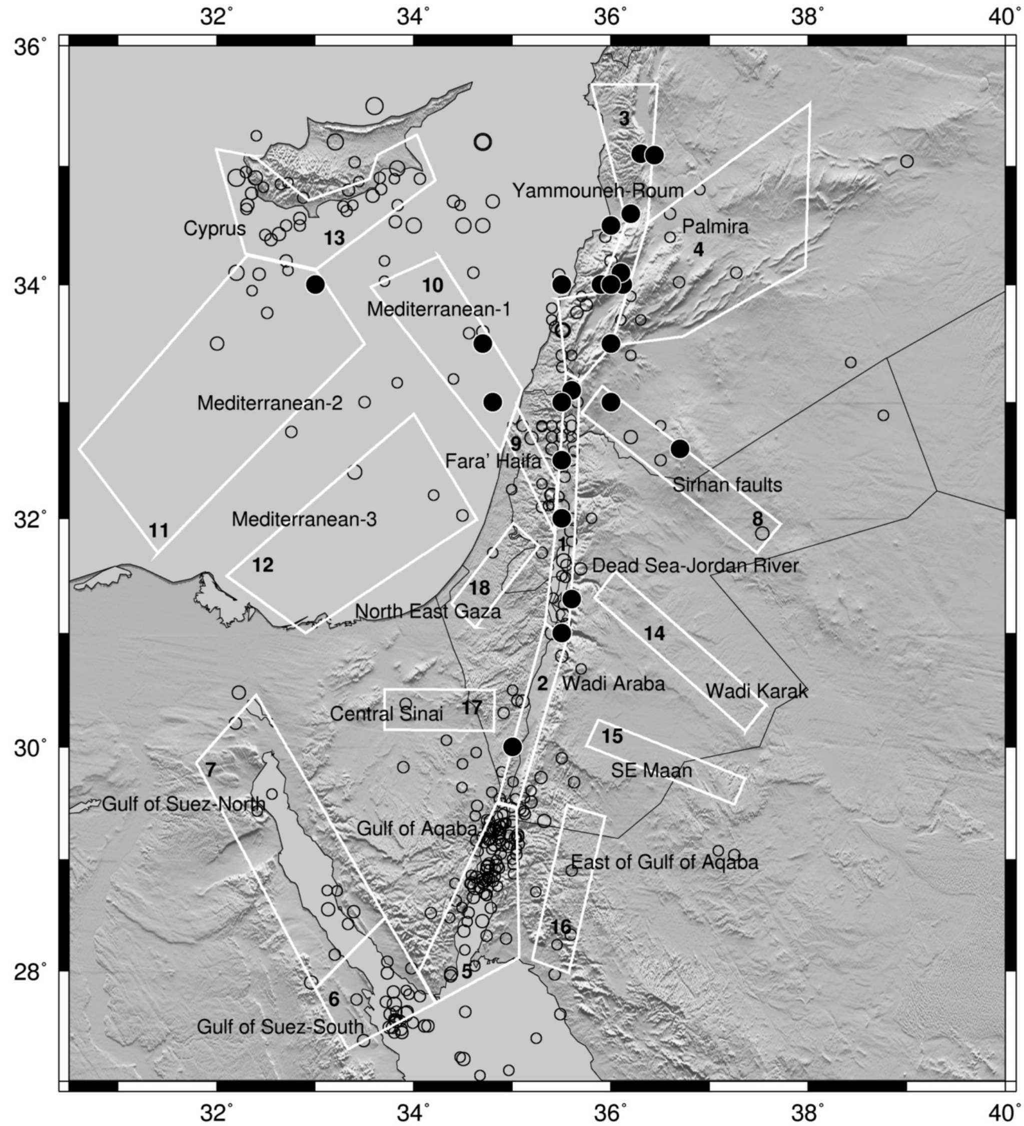

Fig. 2 - Seismic source model consisting of 18 seismogenic sources (numbering of sources as in Table 1) and seismicity above magnitude 4.0 according to the Jordanian catalogue (see reference in the text). Solid circles correspond to historical events (pre-1900), open circles for events in the 20th century.

Amrat *et al*., 2001; Shamir *et al*., 2001; Shapira and Hofstetter, 2001).

2.3. Attenuation

The model for the prediction of the expected ground motion is an essential element of any seismic hazard assessment and has a strong influence on the hazard results. The identification of an appropriate attenuation relationship can be based on the consideration of general relations valid over large regions or on locally derived relations wherever and whenever these are available. It is practically impossible to identify a single model that can be taken as consistently predicting correctly the ground motions, even for those few regions with large databases of strong-motion recordings (Cotton *et al*., 2006). Therefore, usually several ground-motion models are used, combining them through a logic-tree approach, weighting each branch according to the relative confidence in each model (Bommer *et al*., 2005). As the number of ground-motion models increases, the importance of their relative weights on the hazard results decreases, and they become considerably less important than the actual selection of ground-motion models (Sabetta *et al*., 2005; Scherbaum *et al*., 2005). As pointed out by Cotton *et al*. (2006), the ground-motion model selection process should result in the smallest set of independent models that capture the range of possible ground motions in the target region; by following a procedure whereby reasons must be found for exclusion rather than for inclusion.

The instrumental database for strong events is not abundant in the Levant region since very few of these have occurred in recent times. Still, attempts to derive strong motion attenuation relationships and intensity attenuation relationships have been carried out and can be found in the literature (e.g. Ben Menahem *et al*., 1982; Gitterman *et al*., 1994; Husein Malkawi and Fahmi, 1996; Al-Homoud and Amrat, 1998). In general, these relationships are derived from very few instrumental records (implying data gaps both in distance and magnitude), from intensity data and isoseismal information, and in some cases accelerations are mainly derived from seismogram records.

In most of the former studies on seismic hazard assessments for Jordan, the Esteva and Vilalverde (1973) and the Esteva (1974) attenuation relationships were widely used (e.g. Yücemen, 1995; Al-Homoud and Husein Malkawi, 1995; Al-Tarazi, 1999). Among the more general attenuation relationships developed worldwide, European attenuation relationships are based on data sets that contain records from the Middle Eastern countries including Turkey, Israel, Armenia and Iran. Leonov (2001) compares a collection of 12 general attenuation relationships derived in the 1990s with the acceleration data of the 1995 M_w 7.2 Aqaba earthquake as recorded in Israel and finds four of them to be more appropriate than the rest. Among these four the Ambraseys *et al*. (1996) is the only one based on European data and was derived after checking the peak accelerations from digital records, incorporating relations in terms of acceleration response spectra, and good magnitude coverage for the M_S range 4.0-7.3 (Cotton *et al*., 2006). Reported acceleration values in the Aqaba region due to the 1995 M_w 7.2 in the Gulf of Aqaba (the strongest ever recorded instrumentally in the region) agree well with the predicted values of Ambraseys *et al*. (1996) (see Elnashai and El-Khoury, 2004). Thus, the Ambraseys *et al*. (1996) attenuation relationship has been selected to perform the hazard analysis in this study. Following Cotton *et al*. (2006), the hazard results' sensitivity to the choice of the attenuation model was explored by comparing the results with those obtained considering the Boore *et al*. (1997) attenuation relationship, which according to Leonov (2001) is also adapted to the Levant region and used in national hazard maps in the region.

3. Computation procedure

Hazard computations using the SEISRISK III computer code (Bender and Perkins, 1987) have been performed for the area stretching from 28°N and 34°N, and longitudes 33.75°E and 40°E, over an approximately 0.1º x 0.1º regular grid interval (around 9 km) with a total number of computation nodes of 3355. Earthquake location uncertainty is modeled by considering soft boundaries in the seismogenic sources (5 km for SZs 1, 2, 3, 5, and 9; 10 km for SZs 4, 6, 7, 8, 12,13 14 15 16 and 18; 20 km for SZs 10,11, and 17).

The attenuation relationships for *PGA* and *SA* in Ambraseys *et al*. (1996) were used to compute expected ground motion at the nodes of the defined grid. Additionally, the model by Boore *et al*. (1997) was tested for comparison, as referred to in the previous section.

The computations were carried out for *PGA* and *SA*, for 0.1 s, 0.2 s, 0.3 s, 0.5 s, 1.0 s and 2.0 s period, at a 10% probability of exceedance in 50 years, and for rock sites.

The ground motion parameters, the probability level, and the soil type selected correspond to the requirements in the revision and update of the Jordanian building codes.

4. Hazard results

Among the different hazard maps calculated, Figs. 3, 6, and 7 show the probabilistic hazard maps for a 10% probability of exceedance in 50 years, equivalent to a mean return period of 475 years, in terms of *PGA*, and *SA* at 0.2 s and 1.0 s, for rock sites, using Ambraseys *et al*. (1996) ground motion model. The values are given in gravitational acceleration units (g) considering the standard deviation (sigma) in the logarithm of the ground motion parameter.

The absolute maximum, in the three mapped ground motion parameters, appears in the north-western part of the region, in Lebanon; while there are two relative maxima in the Jordanian territory, one to the north, with elongated shape extending from the Dead Sea to the Sea of Galilee, and a second one to the south, around the Gulf of Aqaba. These most hazardous areas reflect the main active segments in the DSF system, to the north of the Dead Sea and around the Gulf of Aqaba; reflecting in between, as well, the less active Araba valley region. Maximum *PGA* values, within Jordanian territory for a 10% probability of exceedance in 50 years, range between 0.25 and 0.30 g. Maximum spectral acceleration values at 0.2 s and 1.0 s are in the range of 0.6-0.7 g and 0.15-0.20 g, respectively.

For comparison, Fig. 4 depicts hazard results in terms of *PGA* for a 10% probability of exceedance in 50 years, and for rock sites, using the Boore *et al*. (1997) ground-motion model. While the expected ground motion distribution is quite similar, the maximum values are lower (around 20%) than those obtained by considering Ambraseys *et al*. (1996), which is consistent with the lower ground-motion values at short distances given by Boore *et al*. (1997) in comparison to those by Ambraseys *et al*. (1996).

Fig. 5 compares site-specific analysis in terms of *PGA* for Amman and Aqaba using both ground-motion models. Both models provide very similar results for annual rates of exceedance lower than 0.01 (i.e. mean return periods longer than 100 years). For the probability levels of engineering interest (e.g. 10% or 2% probability of exceedance in 50 years) the differences in *PGA* values are negligible.

In general, the shape and the hazard values obtained are comparable with those found in previous studies, both at national and regional scales (e.g. Al-Tarazi, 1994, 1999; Husein Malkawi *et al*., 1995; Yücemen *et al*., 2005). Relatively significant differences arise when comparing with models using line sources (e.g. Husein Malkawi *et al*., 1995; Yücemen *et al*., 2005), and also when different ground-motion models are used (e.g. Malkawi *et al*., 1995; Al-Tarazi, 1999). Seismogenic models based on line sources give systematically higher values than area source models at sites close to the line trace, but they remain similar at short distances from

Fig. 3 - Seismic hazard map for the Jordanian region using Ambraseys *et al*. (1996) *PGA* relationship. *PGA* is assessed for a 10% probability of exceedance in an exposure time of 50 years and for rock sites.

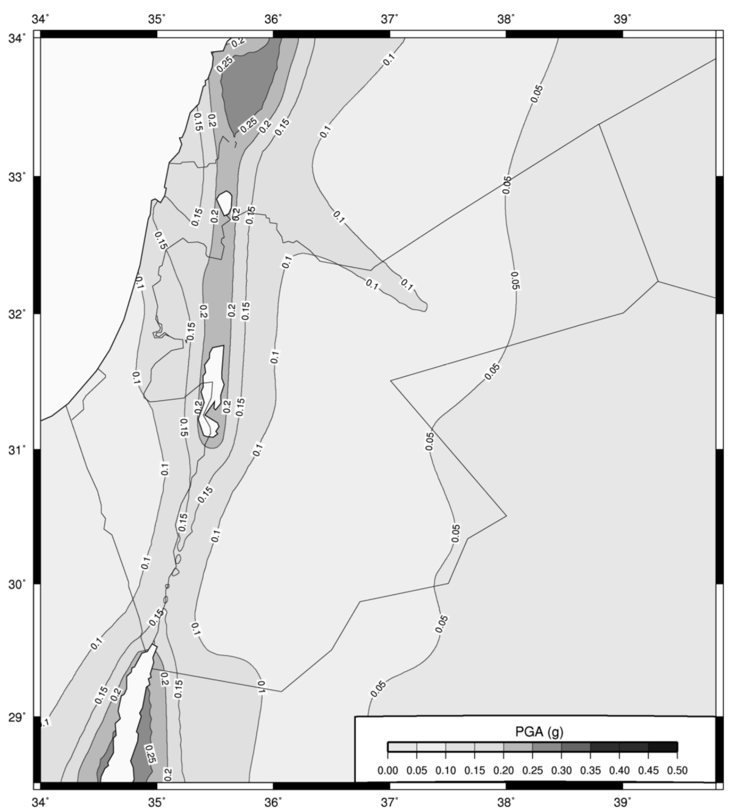

Fig. 4 - Seismic hazard map for the Jordanian region using Boore *et al*. (1997) *PGA* relationship. *PGA* is assessed for a 10% probability of exceedance in an exposure time of 50 years and for rock sites.

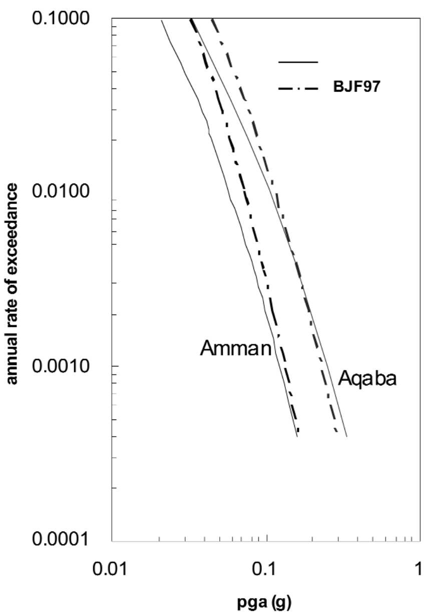

Fig. 5 - Site specific hazard for Amman and Aqaba in terms of *PGA*, comparing Ambraseys *et al*. (1996) and Boore *et al*. (1997) ground motion models.

the line (Bender, 1984, 1986).

The approach followed was considered the most suitable to obtain representative ground motion values of the hazard level for seismic zonation purposes related to national building code regulations.

5. Macrozonatin and response spectra for Jordan

Due to the lack of information at the time, the Jordanian Code for Earthquake-Resistant Buildings (Jordanian National Building Council, 2005), blindly adopted the design response spectrum of the 1997 Uniform Building Code, UBC (International Conference of Building Officials, 1997). The Jordanian code provided values for the seismic coefficients C_a and C_v that were suggested based on soil type and seismic zone factor Z. Values for the Z factor are determined from a zonation map that divides Jordan into four seismic zones, namely 1, 2A, 2B and 3 with corresponding Z values of 0.075, 0.15, 0.2 and 0.3, respectively. However, with the recently acquired information on seismic hazard in Jordan (subject of this paper), a new macrozonation map and a set of relevant response spectra were developed.

The Jordanian territory was initially divided into five different zones, as shown in Fig. 8, and an elastic response spectrum was developed for each zone. The design response spectrum was constructed by anchoring the UBC's response spectrum shape to the values of *SAs* obtained from the probabilistic seismic hazard analysis for the 10% probability of exceedance using Ambraseys *et al*. (1996) attenuation model. Despite the general belief that such spectrum shapes may be unconservative in the long-period range for large magnitudes and distances, the appropriateness of this spectrum shape for Jordan cannot be assessed without carrying out a de-aggregation of

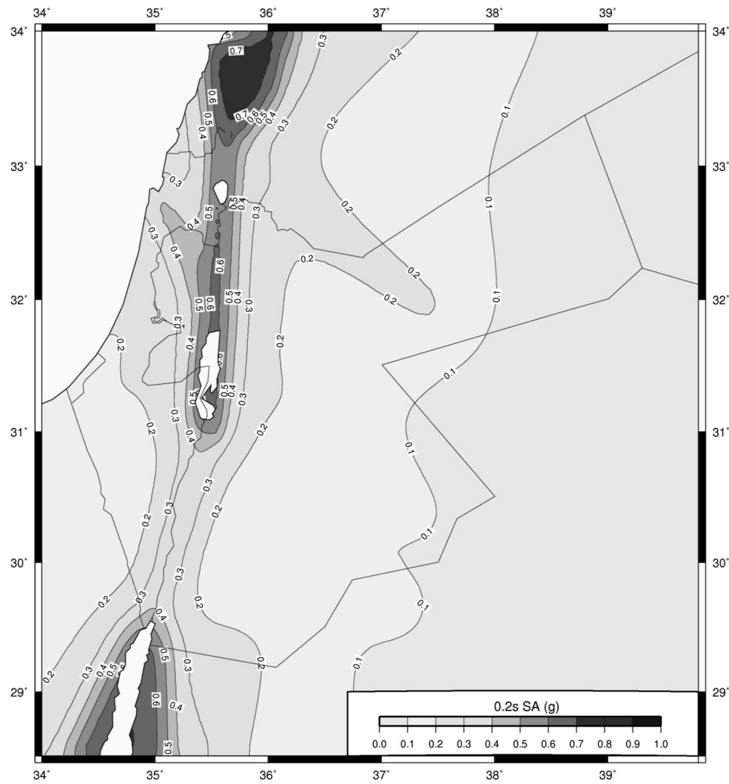

Fig. 6 - Seismic hazard map for the Jordanian region using Ambraseys *et al*. (1996) *SA* relationship at 0.2 s. *SA* (0.2s) is assessed for a 10% probability of exceedance in an exposure time of 50 years and for rock sites.

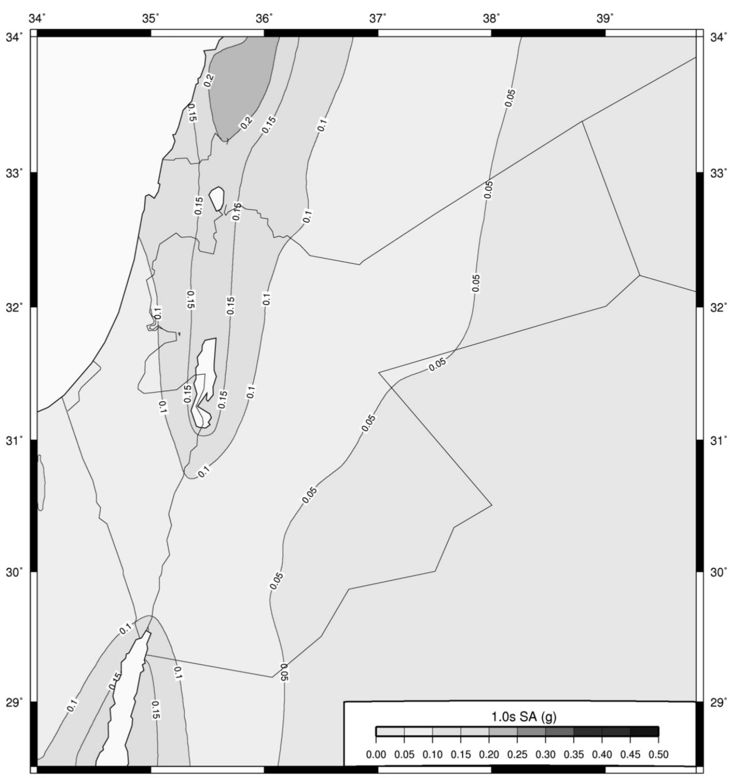

Fig. 7 - Seismic hazard map for the Jordanian region using Ambraseys *et al*. (1996) *SA* relationship at 1.0 s. *SA* (1.0s) is assessed for a 10% probability of exceedance in an exposure time of 50 years and for rock sites.

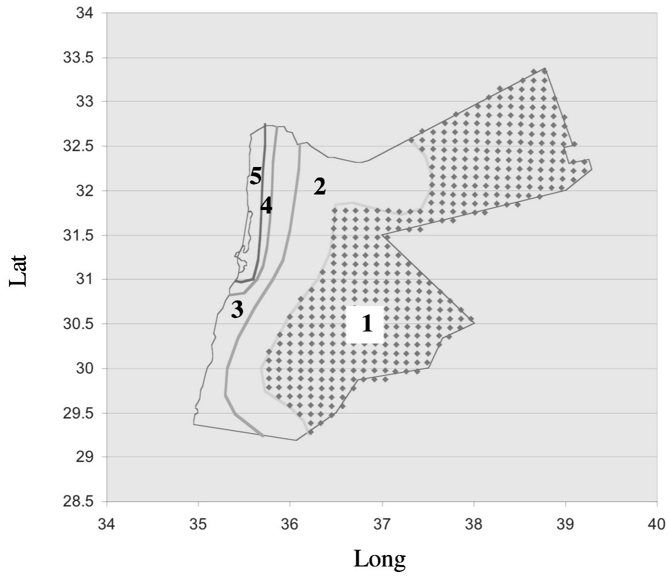

Fig. 8 - Initial zoning suggested for Jordan with the computation nodes of Zone 1.

hazard (detailed analysis of the probabilistic seismic hazard analysis results) to determine the dominant magnitude and distance contributions to the seismic hazard (US Army Corps of Engineers, 1998). Furthermore, this specific shape was adopted in this study so as to compare it with the current Jordanian code spectrum and, hence, the notation of the Uniform Building Code, which is also the notation of the Jordanian code, was used [see Eqs. (1) and (2)].

Considering soil type S_B, (site class rock, V_s>750 m/s as per soil classification of the Jordanian code and UBC), for which the hazard values were computed, the spectral acceleration of the UBC spectrum is given (in terms of the gravitational acceleration, g) by four equations of a linear single degree of freedom system for four intervals of the vibration period (T):

$$\text{for} \quad \begin{array}{ll} T=0 & SA=C_a \\ 0<T<T_o & SA=((2.5C_a-C_a)\ T/T_o)+C_a \\ T_o \leq T \leq T_s & SA=2.5C_a \\ T>T_s & SA=C_v/T \end{array} \qquad (1)$$

$$\text{where} \quad \begin{array}{l} T_s=C_v/2.5C_a \\ T_o=0.2T_s \end{array} \qquad (2)$$

C_a and C_v are numerical coefficients for the soil type under consideration.

It should be noted that the C_a and C_v values are equal for soil type S_B.

Hence, the SA values obtained from the hazard analysis were plotted versus the period of vibration. For each of the six periods of vibration (0.1, 0.2, 0.3, 0.5, 1.0 and 2.0 s) the spectrum ordinate (SA value) was computed as the average of the SA values for all nodes within the zone. In each zone, two calculated SA values were plotted for the same period, that is the average and

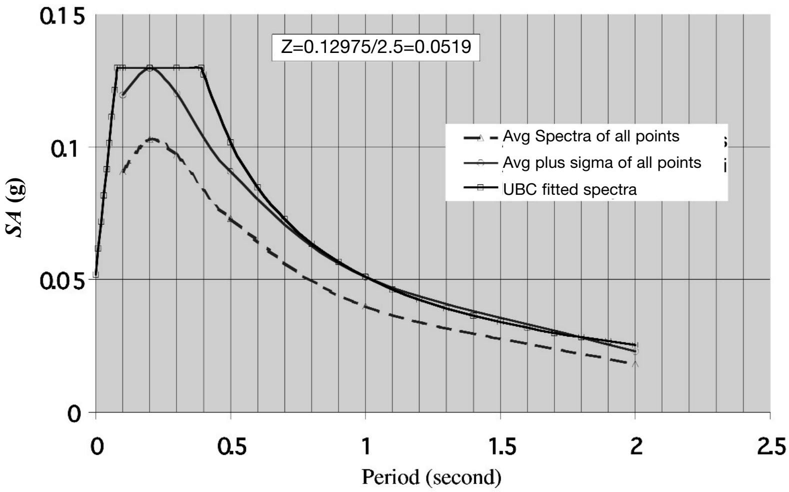

Fig. 9 - Spectrum fitting for Zone 2 based on computed *SA* values.

the average plus sigma of the median *SA* values resulting from the hazard computations. The *SA* values were connected by a smooth line. In the eastern zones of the country (zones 1 and 2 in Fig. 8) the computed *SA* values were relatively low. Therefore, the shape of the UBC spectrum was fitted as an upper envelope to the average plus sigma curve thereby providing conservative design values over the whole range of periods considered as shown in Fig. 9 which displays the spectrum that fits for Zone 2. On the other hand, hazard computations in the central and western zones of

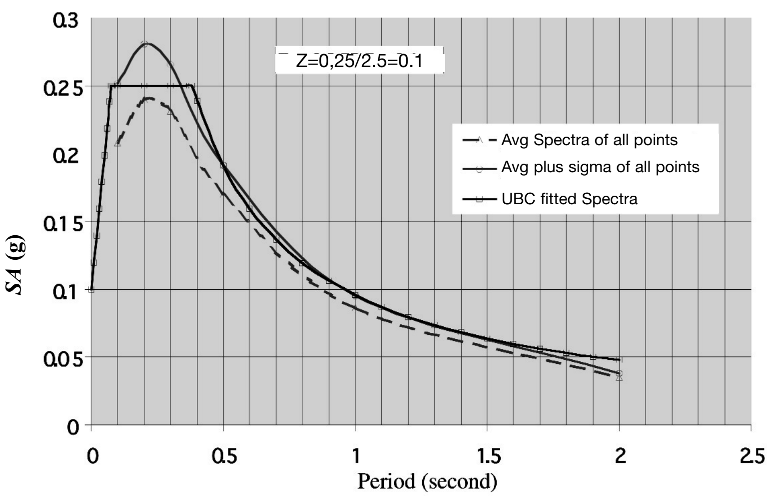

Fig. 10 - Spectrum fitting for Zone 4 based on computed *SA* values.

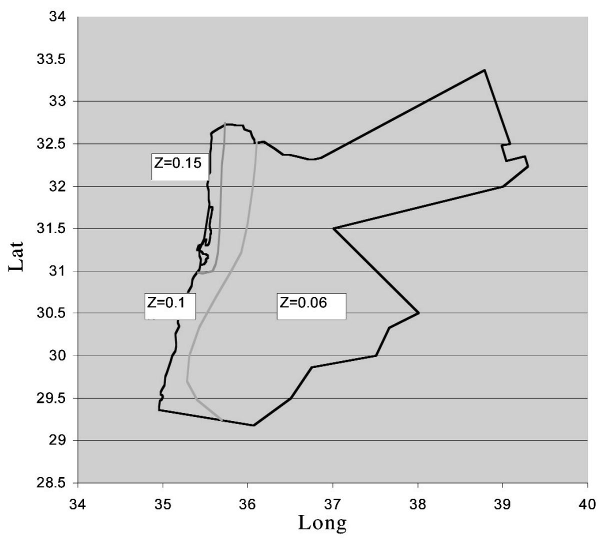

Fig. 11 - Proposed macrozonation map for Jordan.

Jordan exhibited higher *SA* values. Therefore, in fitting the UBC spectrum to the computed spectrum, the spectral envelope was chosen based on the response spectra using both average and average plus sigma values with a less conservative, yet realistic, fit in the medium period range. Spectrum fitting for Zone 4 is shown in Fig. 10 where the constant acceleration segment of the spectrum is set below the computed average plus sigma values for 0.2 and 0.3 s periods.

The values for the seismic zone factor *Z*, which is directly related to the effective *PGA,* were taken equal to 40% of the value of the fitted spectrum plateau [see Eq. (3)] rather than 40% of the short period *SA* where the latter value is usually considered equal to the spectral acceleration for *T*=0.2 s:

$$Z = \text{value of the fitted spectrum plateau} / 2.5. \quad (3)$$

Table 2 - Initial seismic zones and associated response spectrum values.

Zone	*SA*[a] (T= 1 s)	*SA*[a] (T= 0.2s)	Plateau Value[b]	C_a	C_v	T_o (s)	T_s (s)	Computed *Z* value[d]	Suggested *Z* value
1	0.0338	0.0817	0.0820	0.0327	0.0338	0.0830	0.413	0.033	0.06
2	0.0509	0.1297	0.1297	0.0519	0.0509	0.0785	0.392	0.052	0.06
3	0.0703	0.2288	0.2100	0.0840	0.0703	0.0670	0.335	0.084	0.10
4	0.0954	0.2805	0.2500	0.1000	0.0954	0.0760	0.382	0.100	0.10
5	0.1222	0.3993	0.3700	0.1480	0.1300	0.0660	0.330	0.148	0.15

[a] Average plus sigma values in terms of g
[b] *SA* value in terms of g of the plateau of the fitted spectrum
[c] This value was chosen slightly higher than *SA* (T=1 s) to provide a better fit of the spectrum in the long period range
[d] As computed from Eq. (3)

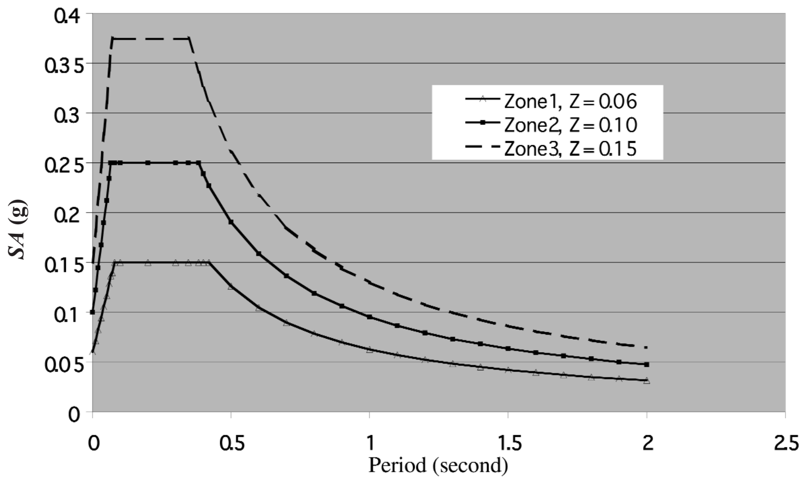

Fig. 12 - Proposed response spectra for the three seismic zones suggested in the macrozonation map for Jordan.

The resulting *Z* values, given by Eq. (3), for the five zones are summarized in Table 2 in addition to the corner periods for the fitted spectral envelope.

Although the computed *SA* values in the eastern part of Jordan were relatively small (resulting in a small *Z* value), the seismic zone factor *Z* was set to a threshold value of 0.06 in the two most eastern Zones (zones 1 and 2 in Fig. 8).

Based on the results presented in Table 2, Zones 1 and 2 were merged into a single zone with a *Z* factor of 0.06. Similarly, the two central zones, zones 3 and 4, were merged into a unified zone with a *Z* factor of 0.10 whereas Zone 5 was assigned a *Z* value of 0.15. Fig. 11 presents the final macrozonation map suggested for Jordan, whereas the proposed response spectra for the three suggested seismic zones are displayed in Fig. 12. Table 3 summarizes the information on the proposed response spectra for the three seismic zones.

Ultimately, the seismic zone factors suggested in this study turn out to be lower than the relevant values given in the current seismic code for the same geographical area. Although the shape of the proposed spectrum is similar to the code spectrum, the difference in corner period values and the maximum *SA* values (plateau values) suggest a difference in the frequency content

Table 3 - Final seismic zones and associated response spectrum values.

Zone Number	C_a	C_v	T_o (s)	T_s (s)	Z value
1	0.06	0.0600	0.079	0.420	0.06
2	0.10	0.0954	0.067	0.382	0.10
3	0.15	0.1300	0.070	0.347	0.15

of the spectrum, especially in the lower period range. It is worth noting that local site effects still need to be incorporated into the set of response spectra proposed in Fig. 12, which is only valid for rock sites. To this end, studies incorporating soil amplification effects in the probabilistic seismic hazard analysis through the use of attenuation models that are applicable to different soil conditions are needed. Alternatively, microzonation studies that assess the modifying influence of the soil column on the ground motion are needed to arrive at a set of response spectra that will be readily available for the use of the structural engineer at the foundation level.

In view of available data and until further, refined information can be gathered on attenuation models suitable for the local geology and crustal formations in Jordan, the results of this assessment instigate robust and long-term strategies for the mitigation of seismic hazard in Jordan. Future efforts should be directed towards the verification of historical seismic events embodied in the seismic catalogue as these major events have a great impact on the seismic parameters, specifically M_{max}, derived for the different sources and thereby on the computed hazard values.

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