Deaggregation of Probabilistic Ground Motions for Selected Jordanian Cities

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ABSTRACT

Probabilistic Seismic Hazard Analysis (PSHA) approach was adopted to investigate seismic hazard distribution across Jordan. Potential sources of seismic activities in the region were identified, and their earthquake recurrence relationships were developed from instrumental and historical data. Maps of peak ground acceleration and spectral accelerations (T=0.2 and T=1.0 sec.) of 2% and 10% probability of exceedance in 50 years were developed. This study deaggregated the PSHA results of 2% and 10% probability of exceedance in 50 years results of twelve Jordanian cities to help understand the relative control of these sources in terms of distances and magnitudes. Results indicated that seismic hazard across these cities is mainly controlled by area sources located along the Dead Sea Transform (DST) fault system. Cities located at short distances from the DST tend to show close deaggregation behavior. Some discrepancies may exist due to the proximity or remoteness of these cities relative to the DST seismic sources and local seismicity. The modal or most probable distance distribution indicated that the distance to the earthquake which contributes most to the hazard at each city is mainly controlled by shaking along faults associated with near seismic area sources. The influence of adjacent seismic sources to the seismic hazard of each city is more evident for the long period spectral acceleration. Distant sources, such as the eastern Mediterranean, Cyprus, Suez and the southern region of the Gulf of Aqaba are relatively low, but can not be neglected due to the intrinsic uncertainties and incomplete seismic data.

KEYWORDS: Seismic hazard, Deaggregation, Ground motion, Jordan.

INTRODUCTION

The Dead Sea Transform (DST) fault system has been the locus of seismic activity with a long history of destructive earthquakes (M>7), surface faulting and landscape changes (Sbeinati et al., 2005; Ferry et al., 2007). Significant archaeological and historical evidences together and recent field studies clearly delineate the damaging effects of historic earthquakes of the region that are mainly related to the DST (Abou Karaki, 1987; Ben-Menahem, 1991; Al-Tarazi, 1992; Malkawi and Alawneh, 2000).

The experience gained from recent and historic earthquakes of the region and the valued knowledge acquired through ongoing research are significantly enhancing our understanding to the DST earthquakes. This knowledge is very crucial for the assessment of

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seismic hazard and risks, the development of earthquake designs and subsequent disaster mitigation plans.

The estimation of detailed earthquake hazards involves the quantitative estimation of ground shaking hazards in a particular area. This is accomplished probabilistically where uncertainties in earthquake size, location and time of occurrence are explicitly considered, or deterministically according to a particular earthquake scenario (Kramer, 1996). Seismic sources, seismicity models, attenuation of strong ground motion parameters and soil conditions are among the key inputs for such studies. Earthquake hazard analysis involves the determination of ground motion parameters such as Peak Ground Acceleration (PGA) and spectral acceleration (i.e. response acceleration) for a given area or specific site location, which are important parameters for the design of civil engineering structures.

In Probabilistic Seismic Hazard Analysis (PSHA), an attempt is made to evaluate site ground motions for selected values of the probability of ground motion exceedance in a design period of the structures or for selected values of annual frequency or return period for a ground motion to be exceeded (McGuire, 1978). PSHA method was initially developed by Cornell (1968) and developed later by McGuire (1978) and Algermissen and Perkins (1976).

The probabilistic approach offers a rational framework for risk management by taking account of the frequency or probability of exceedance of the ground motion against which a structure or facility is designed. The occurrence of earthquakes in a seismic source is assumed as the Poisson distribution. The probability distribution is defined in terms of the annual rate of exceeding the ground motion level at the site under consideration, due to all possible pairs of magnitude and epicentral distance (M,R) of the earthquake event expected around the site. Moreover, the results of PSHA can be exploited to determine predominant sources of seismic hazard and can provide deterministic design magnitudes and distances through a process known as seismic hazard deaggregation processes (Harmsen and Frankel, 2001).

Deaggregation procedure is evolving as an essential tool to understand seismic hazard (McGuire, 1995; Bazzurro and Cornell, 1999; Harmsen et al., 1999). It enables partitioning of the total hazard into contributions based on distance and magnitude. Moreover, it helps bridge the gap between seismic hazard and the design earthquake required for engineering purposes (McGuire, 1995). Essential contributions to seismic hazard deaggregation procedure and applications are found in Stepp et al. (1993), Chapman (1995), McGuire (1995) and Bazzurro and Cornell (1999). This study attempts to use the deaggregation technique to investigate the results of the probabilistic seismic hazard analysis for twelve major Jordanian cities: Amman, Zarqa, Irbid, Ajlun, Jarash, As-Salt, Al-Mafraq, Madaba, Karak, Tafela, Ma'an and Aqaba. These cities are characterized by their higher population and large urban centers (Department of Statistics, 2004).

METHODOLOGY

The methodology of this study is based on five main components: a) delineating earthquake sources, b) defining the potential distribution of seismicity for each of these sources (magnitude frequency distributions), c) calculating the potential ground motions from attenuation relations for all the model earthquakes, d) probabilistic seismic hazard analysis (PSHA) and e) seismic hazard deaggregation.

a. Earthquake Sources

The Dead Sea Transform (DST) fault system is the major tectonic feature dominating the Middle East region (Figure 1). It represents a NNE-trending boundary between the Arabian plate in the east and the Sinai-Palestine subplate to the west. The DST is the major tectonic feature controlling the stratigraphic and structural evolution of the region since the Miocene that resulted in a total horizontal displacement 105 km (Quennel, 1959; Freund and Garfunkel, 1968).

A prerequisite for PSHA is to define existing zones of seismic sources within the region of interest. An earthquake catalogue of seismic events which originated within an area of about 300 km around central Jordan was assembled to represent the temporal and spatial distribution of seismic activity in and around the DST region. The earthquake catalogue of the DST region and adjacent regions is divided into two main categories; historical and instrumental. The available catalogue was carefully reviewed for uncertainties and completeness. Magnitudes were unified in terms of moment magnitude (Mw). Moreover, foreshocks, aftershocks and events of moment magnitude of less than 4 were discarded. The resulting catalogue represents an updated version for the DST region as of February 2008.

Table 1. Seismic sources and their related attributes: area, number of events, mean depth, maximum depth, maximum magnitude and source parameters (a and b values, and activity rates).

Zone name	Area (km^2)	No. of events	Mean depth (km)	Min. depth (km)	Max. depth (km)	Min. Mag.	Max. Mag.	a-value	b-value	α–value*	β- value**	Activity Rate $\lambda 4$***
Mediterranean I	24,141	14	24	5	40	4	7.5	2.0	-0.73	4.61	1.68	0.167
Mediterranean II	21,191	12	27	5	40	4	7.5	-1.35	-0.23	-3.11	2.74	0.164
Mediterranean III	24,397	15	22	5	40	4	7.5	1.13	-0.49	-2.60	1.13	0.179
Cyprus I	26,223	60	33	5	75	4	7.5	1.04	-0.36	2.39	1.59	0.678
Cyprus II	19,332	11	41	5	40	4	7.5	-1.39	-0.19	-3.2	0.90	0.073
Yammuneh	12,791	21	11	5	33	4	7.5	-0.91	-0.20	-2.10	1.60	0.149
Roam	3,632	18	6	5	33	4	7.5	-0.81	-0.35	-1.87	1.47	0.168
Palmiride	24,479	16	9	5	33	4	7.5	-0.59	-0.34	-1.36	3.27	0.173
Jordan Valley	3,653	25	11	5	33	4	7.5	0.41	-0.60	0.94	1.88	0.233
Karmel-Wadi Far'a	2,530	10	9	5	20	4	7.5	-1.22	-0.28	-2.81	1.34	0.089
Dead Sea	2,422	17	16	5	35	4	7.5	-0.42	-0.42	-0.97	1.57	0.188
Wadi Araba	5,609	11	16	5	33	4	7.5	-1.09	-0.23	-2.51	1.68	0.111
Aqaba I	2,342	17	11	5	25	4	7.5	3.24	-0.88	7.50	2.03	0.944
Aqaba II	2,627	23	5	5	25	4	7.5	2.63	-0.71	6.10	1.64	1.150
Aqaba III	5,703	12	7	5	25	4	7.5	4.19	-0.80	9.65	1.84	1.333
Suez	36,981	19	16	5	33	4	7.5	2.79	-0.79	6.42	1.82	0.559

** α–value = a*ln(10), ** β–value = b*ln(10), *** $\lambda 4 = n4/t$ (t=period in years).*

The seismic sources of the DST region are relatively well defined along the DST plate boundary and associated fractured zones. For the purpose of this study, a very conservative approach was followed to define the seismicity of the DST region. A definite number of seismic area sources of significant activity was characterized by dividing the region into discrete homogeneous seismic sources. Seismic area sources approach was followed due to the lack of detailed information about the behavior of existing fault structures with depth.

Historical and instrumental seismicity information clearly demonstrate that most of the earthquake activity seems to be concentrated along the major tectonic features in the DST. These structural features include: the Gulf of Suez, the Gulf of Aqaba, Wadi Araba, the Dead

Sea and the Jordan Valley, Southwest Syria and Central Lebanon and Eastern Mediterranean Region and Cyprus. Based on geology, local and regional tectonic features associated with the DST and historical and instrumental seismic data, 16 different seismic area sources were defined, following the approach given by Jimenez et al. (2005). Figure 2 shows the distribution of historic and instrumental earthquakes of magnitudes (Mw) ≥ 4 of the DST region for the period from 19 AC–February 2008 and their associated seismic area sources.

Table 2. Ground motion values encountered within selected Jordanian cities for PGA and SA (T=0.2 and 1.0 sec.) for 10% and 2% exceedance probability in 50 years, and their ratios.

City	Lat.°	Long.°	10% exceedance probability in 50 years			2% exceedance probability in 50 years			Ratio (2% /10%)		
			PGA (g)	SA (g) (T=0.2 s)	SA (g) (T=1.0 s)	PGA (g)	SA (g) (T=0.2 s)	SA (g) (T=1.0 s)	PGA	SA (T=0.2 s)	SA (T=1.0 s)
Aqaba	29.52	35.01	0.22	0.46	0.14	0.37	0.82	0.28	1.6	1.8	2.0
Ajlun	32.33	35.75	0.26	0.55	0.15	0.42	0.98	0.35	1.7	1.8	2.3
As-Salt	32.04	35.73	0.25	0.54	0.15	0.42	0.97	0.34	1.7	1.8	2.3
Madaba	31.72	35.80	0.21	0.48	0.13	0.37	0.91	0.32	1.7	1.9	2.5
Al-Karak	31.19	35.71	0.21	0.48	0.13	0.37	0.91	0.31	1.7	1.9	2.5
Irbid	32.55	35.85	0.21	0.46	0.13	0.36	0.83	0.29	1.7	1.8	2.2
Jarash	32.28	35.90	0.17	0.36	0.10	0.27	0.63	0.21	1.6	1.8	2.1
Amman	31.95	35.92	0.15	0.32	0.10	0.25	0.57	0.20	1.6	1.8	2.1
Tafela	30.84	35.60	0.15	0.32	0.09	0.26	0.59	0.18	1.7	1.9	2.1
Zarqa	32.07	36.09	0.12	0.24	0.08	0.18	0.39	0.15	1.5	1.6	1.9
Al-Mafraq	32.34	36.21	0.11	0.21	0.07	0.16	0.33	0.13	1.5	1.6	1.8
Ma'an	30.20	35.73	0.09	0.17	0.06	0.13	0.26	0.11	1.5	1.6	1.7

b. Magnitude-Frequency Distribution

Seismic activity of a region is characterized in terms of the Gutenberg–Richter (1944) frequency–magnitude recurrence relationship $\log_{10} N = a - bM$, where N stands for the number of earthquakes greater than or equal to a particular magnitude. The a and b parameters which characterize the seismicity of a given region, are calculated by regression analysis for the historical and instrumental data. This required the definition of a maximum magnitude value to set the upper limit in the recurrence relationship, which is a maximum magnitude associated with each seismic sources area.

Based on previous assessments (Arieh and Rabinowitz, 1989; Vered, 1978; Shapira and Hofstetter, 2001), it can be stated that the maximum magnitude along the Dead Sea Transform fault can be assumed to be equal to 7.5. These estimations are based mainly on the limited seismic history and partially on the length of the mapped fault. Subsequently, in correlation with documented historic events of the region and the work of

Shapira and Hofstetter (2001) and Elnashai and El-Khoury (2004), this study assumed a maximum magnitude of 7.5. Table 1 lists the defined seismic area sources and their characteristic seismic parameters.

c. Ground Motion Attenuation Relationships

Empirical ground motion attenuation relationships are generally employed in the quantification of seismic hazard in either deterministic or probabilistic approaches. These relationships describe the change of ground motion severity with source mechanism, distance and local geology. Accordingly, attenuation relationships tend to be regionally specific according to the geological and tectonic structures and faulting styles in the region under study. Furthermore, attenuation relations may be site-specific in the sense that they may be established for particular soil condition; such as rock, soft soil, deep stiff soil, shallow stiff soil,… etc.

Due to the limited strong motion data in Jordan, published empirical ground motion relationships specifically developed for the DST region are not available. However, Ambraseys et al. (1996) relationships for both Peak Ground Acceleration (PGA) and Spectral Acceleration (SA) in terms of surface magnitude (Ms) were found to be appropriate to be used for the DST region. Jimenez et al. (2005) employed the equations of Ambraseys et al. (1996) for the assessment of seismic hazard in Jordan. Leonov (2000) investigated a number of attenuation relations against strong motion data of the 22nd November 1995 Gulf of Aqaba earthquake of magnitude (Mw=7.2) that occurred on the Aragonese fault, 70 km south of the towns of Eilat and Aqaba. He stated that the equations of Ambraseys et al. (1996) and Boore-Joyner-Fumal (Boore et al., 1994) are very representative for the DST region. However, the Boore-Joyner-Fumal (Boore et al., 1994) equation was the most fitting equation for the investigated events. This attenuation relationship is sensitive to local site conditions, where it incorporates a site factor that is essentially a physical characteristic of the local geology by means of a term of average shear wave velocity measured over the upper 30 m. In addition to another term, referring to the fault mechanism type makes this relationship attractively versatile for adoption.

This study investigated the performance of the attenuation equations of Ambraseys et al. (1996) and Boore, Joyner and Fumal (1994 and 1997) for Mw=6 and Mw=7. Figure 3 shows a comparison between these relations against published strong motion data from Jordan and Israel. Strong motion data were complied from Al-Qaryouti (2002) and Gitterman (1999). Since most of the long period fault structures of the DST region have a maximum magnitude of 7.5, these relationships show a very acceptable performance for the seismicity of the region. Accordingly, for Peak Ground Acceleration (PGA) and Spectral Acceleration (SA), Ambraseys et al. (1996) and Boore et al. (1994) models were accepted as appropriate models for evaluation of the ground motion parameters for the DST region.

d. Probabilistic Seismic Hazard Analysis (PSHA)

This study adopted the PSHA approach developed by Cornell (1968) and McGuire (1978). This approach requires the characterization of existing seismic sources, the definition of appropriate ground motion model and the calculation of probabilistic seismic hazard for different sites with ground motions expected with a given probability for a specified interval of time.

The PSHA is conducted using EZ-FRISK™ -7.25, a computer program for earthquake ground motion estimation developed by Risk Engineering, Inc. EZ-FRISK™ assumes that the number of earthquakes occurring on a fault follows a stationary Poisson process.

The characteristics of the defined seismic area sources (Table 1) were incorporated into the software's area fault database. Initially, ground motions were analyzed using the multisite approach of EZ-FRISK™ for the geographic region encompassing Jordan, Israel and Palestine to have more insight on the spatial distribution of ground motions across the region. The ground motion results were estimated on a 0.2° x 0.2° grid and exported into ArcGIS-9.2 for map production. Later, ground motion values of the selected cities were extracted and used in subsequent deaggregation analysis.

Table 3. PSHA deaggregation results in terms of mean and modal magnitudes, distances and epsilon values for PGA, SA (0.2 sec.) and SA (1.0 sec.) at a probability of exceedance of 2% in 50 years.

City	Mag. (Mw)		Distance (km)		Epsilon	
	Modal Mag.	Mean Mag.	Modal Distance	Mean Distance	Modal Epsilon	Mean Epsilon
	PGA					
Aqaba	5.25	6	15	19	1.9	1.4
Ajlun	7.25	6.2	25	20	-0.3	1.3
As-Salt	7.25	6.2	25	21	-0.3	1.2
Madaba	7.25	6.6	25	23	-0.3	0.88
Al-Karak	7.25	6.5	25	22	-0.3	0.94
Irbid	7.25	6.4	25	22	-0.5	1.1
Jarash	7.25	6.5	25	27	-1.1	1.1
Amman	7.25	6.6	25	30	-1.3	1
Tafela	7.25	6.2	25	25	1.5	1
Zarqa	7.25	6.6	45	47	1.7	1.5
Al-Mafraq	7.25	6.6	55	58	1.9	1.7
Ma'an	7.25	6.4	45	73	2.3	1.8
SA (0.2 sec.)						
Aqaba	5.75	6.3	15	19	0.9	0.89
Ajlun	7.25	6.5	25	20	-0.3	0.85
As-Salt	7.25	6.5	25	21	-0.3	0.83
Madaba	7.25	6.7	25	22	-0.5	0.6
Al-Karak	7.25	6.6	25	22	-0.5	0.63
Irbid	7.25	6.6	25	21	-0.7	0.67
Jarash	7.25	6.6	25	25	-1.3	0.63
Amman	7.25	6.7	25	28	-1.5	0.55
Tafela	7.25	6.4	25	24	-1.3	0.55
Zarqa	7.25	6.8	35	42	1.7	0.99
Al-Mafraq	7.25	6.7	45	53	1.5	1.3
Ma'an	7.25	6.5	45	60	1.3	1.2
SA (1.0 sec.)						
Aqaba	7.25	6.7	15	24	1.1	0.68
Ajlun	7.25	6.7	25	21	-1.5	0.29
As-Salt	7.25	6.7	25	21	-1.5	0.26
Madaba	7.25	6.9	25	23	-1.3	-0.011
Al-Karak	7.25	6.9	25	23	-1.7	0.025
Irbid	7.25	6.9	25	23	-1.7	0.18
Jarash	7.25	6.9	25	31	-2.1	0.4
Amman	7.25	7	25	33	-2.1	0.36
Tafela	7.25	6.8	25	32	-2.1	0.37
Zarqa	7.25	7	35	53	1.3	0.94
Al-Mafraq	7.25	7	45	67	1.3	1.2
Ma'an	7.25	7	45	100	1.7	1.4

Table 4. PSHA deaggregation results in terms of mean and modal magnitudes, distances and epsilon values for PGA, SA (0.2 sec.) and SA (1.0 sec.) at a probability of exceedance of 10% in 50 years.

City	Mag. (Mw)		Distance (km)		Epsilon	
	Modal Mag.	Mean Mag.	Modal Distance	Mean Distance	Modal Epsilon	Mean Epsilon
	PGA					
Aqaba	5.25	5.7	15	22	1.1	1.1
Ajlun	5.25	5.7	25	22	1.3	1.1
As-Salt	5.25	5.7	25	23	1.3	1.1
Madaba	5.25	6	25	27	1.5	1
Al-Karak	5.25	5.9	25	25	1.3	0.96
Irbid	5.25	5.8	25	26	1.3	1.1
Jarash	5.25	5.9	25	33	1.7	1.4
Amman	5.25	6	35	38	2.1	1.4
Tafela	5.25	5.8	25	31	1.1	1
Zarqa	5.25	6.1	45	57	2.3	1.6
Al-Mafraq	5.25	6.2	55	69	2.3	1.7
Ma'an	5.25	6.1	55	92	1.9	1.8
SA (0.2 sec.)						
Aqaba	5.25	6	15	23	0.9	0.7
Ajlun	5.75	6	25	22	0.9	0.66
As-Salt	5.75	6	25	23	1.1	0.66
Madaba	5.75	6.3	25	26	0.9	0.52
Al-Karak	5.75	6.2	25	25	0.9	0.48
Irbid	5.75	6.1	25	25	0.9	0.65
Jarash	5.75	6.2	25	32	1.1	0.81
Amman	5.75	6.3	35	37	1.3	0.82
Tafela	5.75	6	25	31	0.9	0.55
Zarqa	5.75	6.4	45	54	1.3	1.1
Al-Mafraq	5.75	6.4	55	65	1.5	1.2
Ma'an	5.75	6.3	55	82	1.5	1.2
SA (1.0 sec.)						
Aqaba	7.25	6.4	15	35	1.1	0.79
Ajlun	7.25	6.3	25	27	-2.1	0.55
As-Salt	7.25	6.3	25	28	-2.1	0.54
Madaba	6.75	6.5	25	33	-2.1	0.4
Al-Karak	6.75	6.4	25	32	-2.1	0.37
Irbid	7.25	6.5	25	35	-2.1	0.61
Jarash	7.25	6.6	35	48	1.1	0.78
Amman	7.25	6.6	35	53	0.9	0.76
Tafela	7.25	6.4	25	56	0.7	0.72
Zarqa	7.25	6.7	45	78	1.1	1
Al-Mafraq	7.25	6.8	55	92	0.9	1.1
Ma'an	7.25	6.8	55	130	1.1	1.3

Table 5. Probable seismic area sources based on the mean distances and magnitudes of each deaggregated ground motion at a probability of exceedance of 2% and 10% in 50 years. Most probable dominating sources are shown in bold face.

City	2% probability of exceedance in 50 years			10% probability of exceedance in 50 years		
	PGA	SA (0.2 sec.)	SA (1.0 sec.)	PGA	SA (0.2 sec.)	SA (1.0 sec.)
Aqaba	**Aqaba I, Wadi Araba**	**Aqaba I, Wadi Araba**	**Aqaba I, Wadi Araba**	**Aqaba I, Wadi Araba**	**Aqaba I, Wadi Araba**	**Aqaba I, Wadi Araba**
Ajlun	**Jordan Valley**	**Jordan Valley**	**Jordan Valley**	**Jordan Valley**	**Jordan Valley**	**Jordan Valley**
As-Salt	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea, Karmel-Wadi Far’a
Madaba	**Dead Sea,** Jordan Valley	**Dead Sea,** Jordan Valley	**Dead Sea,** Jordan Valley	**Dead Sea,** Jordan Valley	**Dead Sea,** Jordan Valley	**Dead Sea,** Jordan Valley
Al-Karak	**Dead Sea,** Wadi Araba	**Dead Sea,** Wadi Araba	**Dead Sea,** Wadi Araba	**Dead Sea,** Wadi Araba	**Dead Sea,** Wadi Araba	**Dead Sea,** Wadi Araba
Irbid	**Jordan Valley**	**Jordan Valley,** Roam, Palmiride	**Jordan Valley,** Roam, Palmiride	**Jordan Valley**	**Jordan Valley,** Roam, Palmiride	**Jordan Valley,** Roam, Palmiride, Karmel-Wadi Far’a
Jarash	**Jordan Valley**	**Jordan Valley**	**Jordan Valley**	**Jordan Valley**	**Jordan Valley,**	**Jordan Valley,** Karmel-Wadi Far’a, Roam, Dead Sea, Palmiride
Amman	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley** Dead Sea Karmel-Wadi Far’a
Tafela	**Wadi Araba**	**Wadi Araba**	**Wadi Araba** Dead Sea	**Wadi Araba**	**Wadi Araba**	**Wadi Araba** Dead Sea
Zarqa	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea	**Jordan Valley,** Dead Sea, Karmel-Wadi Far’a, Roam, Palmiride
Al-Mafraq	**Jordan Valley,** Roam, Palmiride	**Jordan Valley**	**Jordan Valley,** Roam, Palmiride, Karmel-Wadi Far’a	**Jordan Valley,** Roam, Palmiride, Dead Sea	**Jordan Valley,** Roam, Palmiride, Dead Sea	**Jordan Valley,** Roam, Palmiride, Dead Sea, Karmel-Wadi Far’a
Ma'an	**Wadi Araba**	**Wadi Araba**	**Wadi Araba,** Aqaba I, Dead Sea	**Wadi Araba,** Aqaba I	**Wadi Araba**	**Wadi Araba,** Aqaba I, Dead Sea

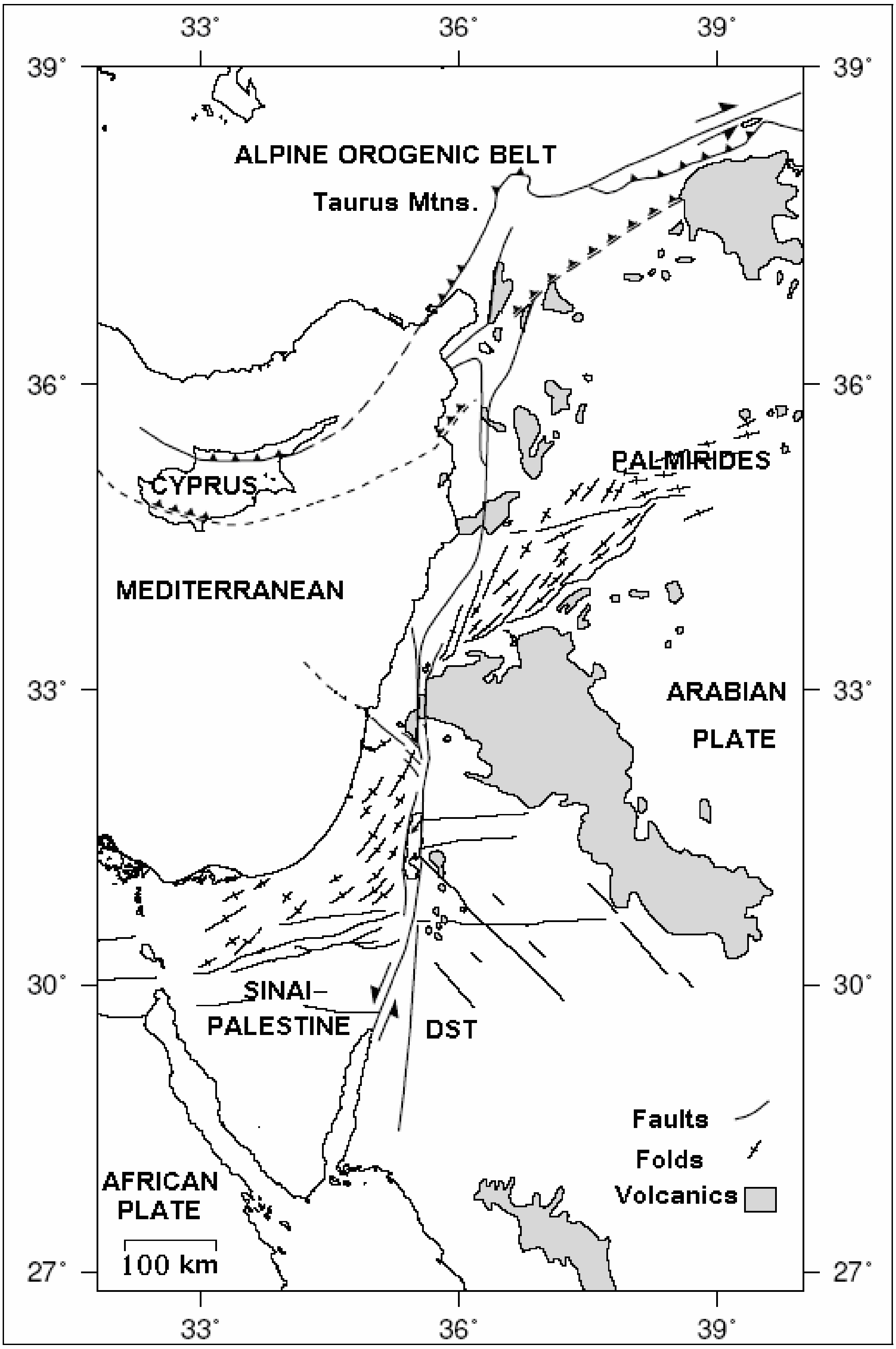

Figure (1): Tectonic map of the Dead Sea Transform and the Syrian Arc Fold Belt showing the location of Amman sheet area (After Garfunkel, 1981).

The PSHA analysis has been conducted for return periods of 475 and 2475 years corresponding to 10% and 2% probability of exceedance in 50 years, respectively. The selected ground motion parameters of analysis were the Peak Ground Acceleration (PGA) and the Spectral Accelerations (SA) at periods of 0.2 and 1 sec. PSHA results using Boore et al. (1994) attenuation relationship were utilized for all sources for the estimation PGA and SA values, whereas the results based on Ambraseys et al. (1996) relationship proved to be erratic at near (< 10 km) and far (>60 km) distances from expected epicenters (Figure 3). Therefore, Boore et al. (1994) relationship was used to estimate the Peak Ground Acceleration (PGA) and the Spectral Accelerations (SA) at periods of 0.2 and 1 sec. values for Jordan which are represented in Figures (4, 5 and 6).

e. Seismic Hazard Deaggregation

In order to have more insight into the probabilistic seismic hazard maps presented earlier, an attempt is made to deaggregate these ground motions for the 12 selected cities. The latitude and longitude for the downtowns of each of these cities are used to deaggregate their ground motions in terms of bin pairs of distance and magnitude (R, M). Deaggregation was carried out based on a magnitude interval of 0.5 and a distance interval of 10 km, following the procedure presented in EZ-FRISK™ software.

For a specific spectral period and ground motion amplitude, seismic hazard can be deaggregated to show the contribution to the annual frequency of exceedance by magnitude (M), distance (R) and the normalized residual (ε), expressed in terms of the number of standard deviations from the median ground motion estimated with a ground motion attenuation relationship (McGuire, 1995; Pagani and Marcellini, 2007).

Deaggregation is becoming a more fundamental procedure to answer the question concerning which sources are significantly contributing to the existing hazard, such as earthquakes taking place near the maximum magnitude on a fault or due to rare ground motions characterized by high ε values. The National Building Code of Canada (NBCC, edition-2005) is recognizing the importance of deaggregation in its design provision that is hoped to lead to improve earthquake-resistant structures (Halchuk et al., 2007).

In general, deaggregation of seismic hazard at high amplitude indicates that large M, small R and large ε are contributing more to this hazard. On the other hand, low amplitudes of ground motion indicate low M, large R and small ε. Ground motions of low frequencies (T=1 sec.) of shaking are usually associated with larger M and larger R than those of high frequencies (T=0.2 sec.) of ground shaking. The term ε of the attenuation relationships, which decreases with the increase in M, tends to shift the contribution to lower magnitude values (Risk Engineering, Inc., 2008).

Deaggregation results can serve as an input for deterministic seismic hazard, by defining needed earthquake scenarios. Additionally, deaggregation can help in the construction of needed design earthquakes. McGuire (1995) mentioned that design earthquakes can be constructed by modification until the computed spectral ordinates replicate the uniform hazard spectrum of any chosen return period. These results can be plotted in terms of what is known as deaggregation plots which can provide useful information on the distance and magnitude of predominant sources, which can be used to generate scenario earthquakes and select corresponding time histories for seismic design.

RESULTS AND DISCUSSION

a. Peak Ground Acceleration (PGA) and Spectral Accelerations (SA)

The results of the hazard analysis represent the median of the log-normal distribution ground motion outputs obtained from computations using the above attenuation relationships on firm-rock conditions (Vs=760 m/s). Figure 4 through Figure 6 show the PGA and SA spatial distribution maps for 5% damping at periods (T=0.2 and 1.0 seconds) with respect to 2% and 10% probability of exceedance in 50 years, respectively. The 475-year and 2475-year seismic hazard maps of the investigated ground motions show relative variability

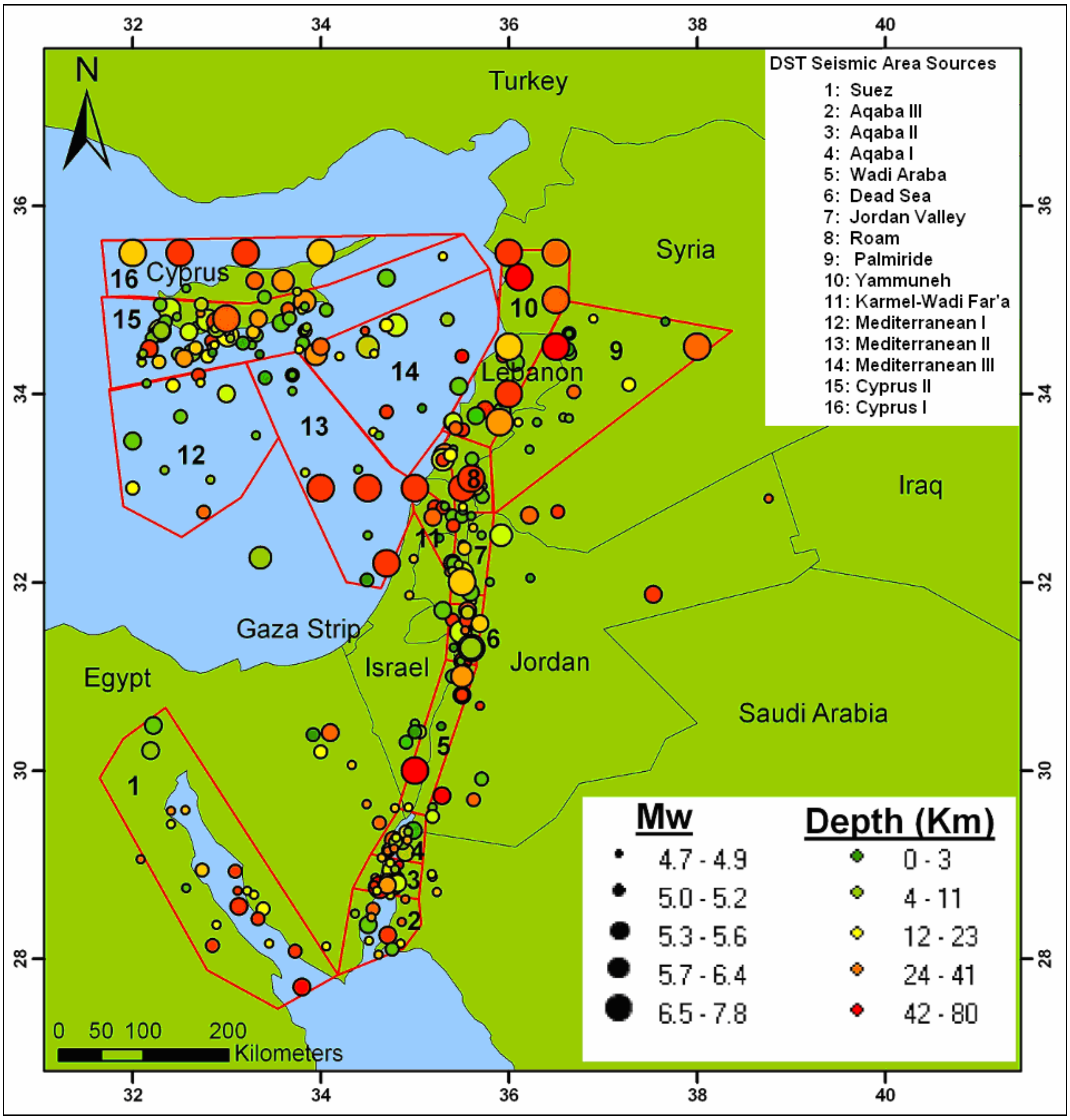

Figure (2): Seismicity map of the Dead Sea Transform region including historic and instrumental data. Area seismic sources are outlined with red border.

among the 12 selected Jordanian cities. This is primarily related to their proximity or remoteness to the DST seismic sources (Figure 2), where elevated ground motions are taking place along the DST and are dominating the vicinity of the Gulf of Aqaba to the south and close to the Dead Sea Basin and Jordan Valley to the north. The northern distinctive pattern of ground motion distributions reflects the influence of the seismicity of the Dead Sea Basin, Jordan Valley, Karmel-Wadi Far'a, Yammouneh and Roam seismic sources on the hazard map of the region, compared to the farthest western sources; i.e. the Mediterranean and Cyprus sources.

Moreover, the ground motion difference between the 10% probability of exceedance and 2% probability of exceedance in 50 years close to the DST fault structures is typically smaller than the difference between the two probabilities in less active seismic areas to the east and west of the DST.

Table 2 shows a list for the ground motion values encountered within each city. These results indicate that all SA values of 2% probability of exceedance in 50 years are much higher than those of the SA of 10% probability of exceedance in 50 years. This may be attributed to the increasing influence of the infrequent but larger magnitude events associated with the DST region.

The provisions of the National Earthquake Hazards Reduction Program (NEHRP, 1997) and the International Building Code (ICC, 2006) provide a minimum conservative margin of about 1.5 times the design earthquake ground motion. This means that if a structure experiences a level of ground motion 1.5 times the design level, the structure should have a low likelihood of collapse.

Table 2 indicates that the spectral acceleration values of the 2% probability of exceedance in 50 years are almost 1.5-2 times more than the 10% probability of exceedance in 50 years ground motion values for most of the selected Jordanian cities. This means that if the 10% probability of exceedance in 50 years map was used as the design ground motion and the 2% probability of exceedance in 50 years ground motions were to occur, there would be low confidence that structures would not collapse due to these larger ground motions. Accordingly, this study strongly suggests the need to acknowledge the 2% probability of exceedance in 50 years spectral accelerations in design practice for the Jordanian cities located in the vicinity of the DST.

b. Seismic Hazard Deaggregation

The deaggregation procedure was carried out for the amplitudes of GPA, SA (T=0.2 sec.), and SA (T=1.0 sec.) at 2% and 10% probability of exceedance in 50 years (Table 2). Tables 3 and 4 present the results of deaggregation in terms of mean and modal (most probable) magnitudes, distances and epsilon values for the above mentioned spectral accelerations. These results show that for the lower probability level (2%), in comparison to the 10% probability level, the dominant earthquake contributing to the ground motion is larger and located closer to each city. Figure 7 shows a comparison between the deaggregation of distance and magnitude of contributing sources at 2% and 10% probability levels for the ground motions encountered at the city of Irbid. At 10% probability of exceedance, deaggregation of 0.13 g at SA (T=1.0 sec.) shows that the mean magnitude of the causative event is equal to 6.5 which is located at a mean distance of 35 km (Figure 7-D). Meanwhile, at 2% probability of exceedance, deaggregation of 0.29 g at SA (T=1.0 sec.) shows that the contributing event is located at a mean distance of 23 km, and has a mean magnitude of 6.9 (Figure 7-B). Moreover, for each probability level, deaggregated distances and magnitudes tend to increase along with the increase of period from 0.2 to 1.0 sec., indicating that the effect of the larger and more distant earthquakes is more pronounced in longer periods more than that in shorter periods. Figure 7-A shows that the deaggregation of 0.83 g at T=0.2 sec. for 2% probability is dominated by an earthquake located at a mean distance of 21 km and its mean magnitude equals 6.6. In general, the significance of distant events increases with the increase in natural periods, since low frequencies (i.e., long-period SA values) attenuate slower with distance than that of the high frequencies (Malhotra, 2003). Accordingly, it is expected that the long period spectral accelerations will reflect the effect of distant sources. Therefore, judging the contribution of proximal or distant earthquake sources requires the careful inspection of short and long periods at different probability levels.

The results of deaggregation are more realized by means of a bar chart representing magnitude, distance and probability density. Each bar represents a seismic event whose size and distance are indicated along the horizontal axes. The height of the bin signifies the relative importance of a particular seismic event according to its probability density.

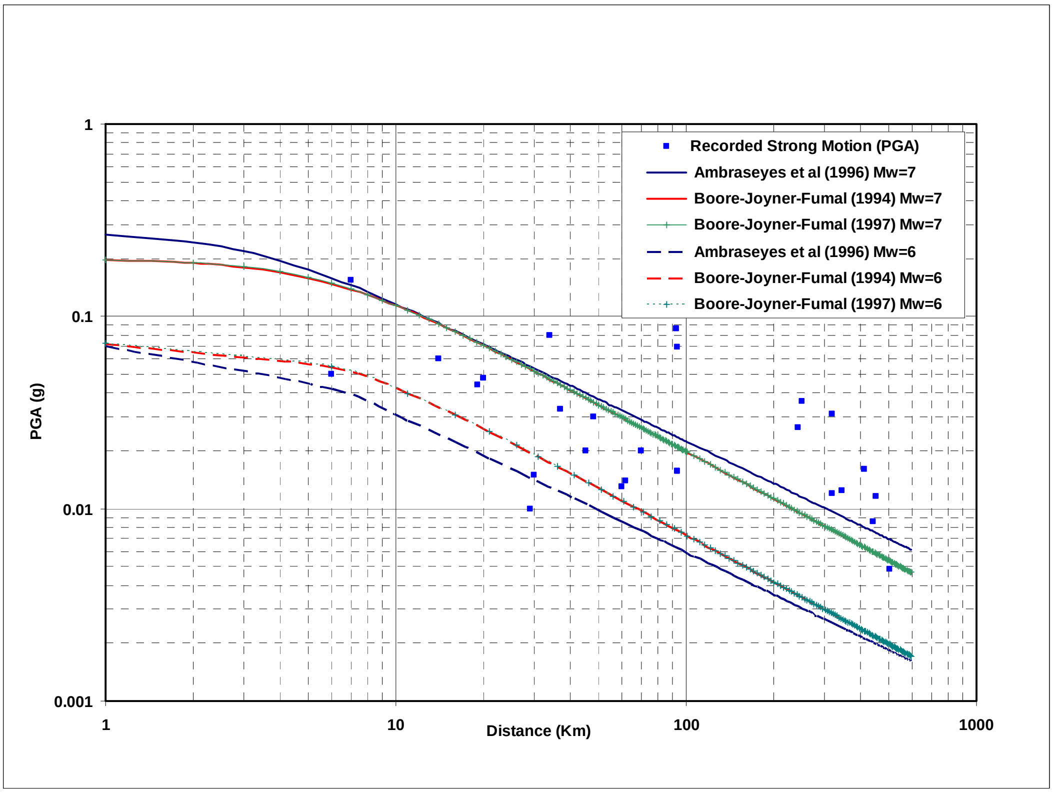

Figure (3): Comparison between the attenuation equations of Ambraseyes et al. (1996), Boore-Joyner-Fumal (1994 and 1997) against GPA values of strong motion stations from Jordan and Israel, using Mw=6 and 7.

These bar charts were prepared for the 12 cities at the two investigated levels of probabilities for PGA and SA (T=0.2 and 1.0 sec.).

Inspection of these figures suggests the possibility to sort these cities into a number of groups based on the shapes of their deaggregation bar charts for both SA (T=0.2 sec.) and SA (T=1.0 sec.). The first group includes Irbid, Ajlun, As-Salt, Madaba, Al-Karak, Jarash, Amman and Tafela. Figure 8 shows the deaggregation results of the city of Ajlun; a typical example of this group. The second group includes Zarqa and Al-Mafraq (Figure 9), while the third group represents all cities displaying dissimilar patterns, and includes Ma'an (Figure 10) and Aqaba (Figure 11).

The mean distance for the controlling earthquake on the cities of the first group is ranging between 20-28 km and between 22-37 km for SA (0.2 sec.) at 2% and 10% probabilities, respectively. Contrary to the fact that the longer the period of ground motion, the more the control is expected from distant seismic sources, the SA (1.0 sec.) mean distance of the controlling events is still very near and ranges between 21-33 km and 27-56 km for 2% and 10% probabilities, respectively. Therefore, at a given probability level, it is clear that for longer periods, some cities will focus their bar chart pattern due to a single controlling source region, and may show a more tailed behavior due to the influence of juxtaposing seismic sources, which are larger and more distant. On the other hand, deaggregation result of the higher probability (10%) will reflect the largest and closest sources (Figure 7). Therefore, seismic hazard of these cities is mainly related to near seismic area sources, whereas the relative contribution from far-field seismic sources to the seimicity of these cities is very limited. The tailing behavior of higher SA periods suggests the effect of distant seismic sources located outside the DST region,

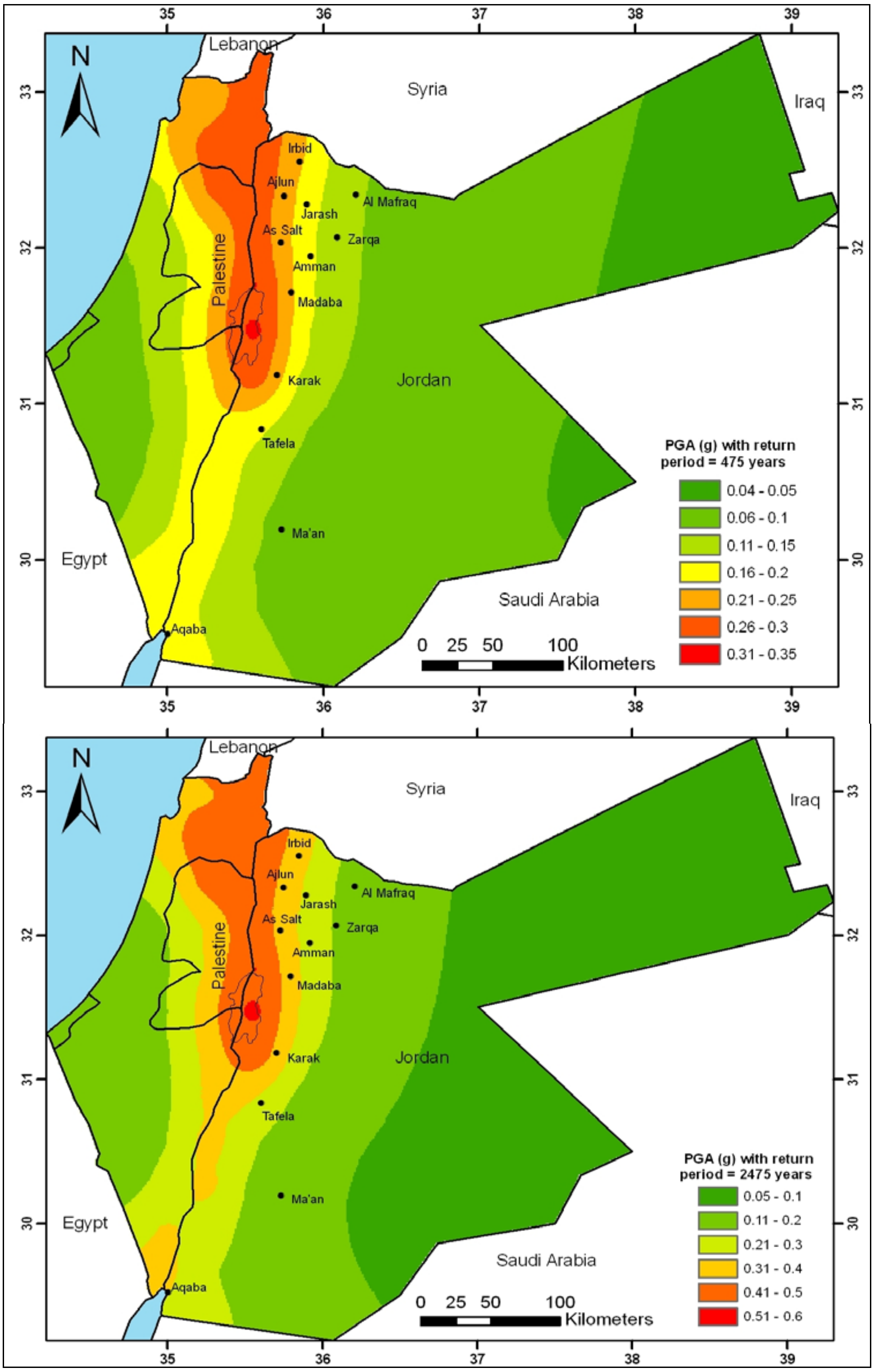

Figure (4): Probabilistic seismic hazard map for peak ground acceleration at 10% (upper) and 2% (lower) probability of exceedance in 50 years on firm-rock site conditions.

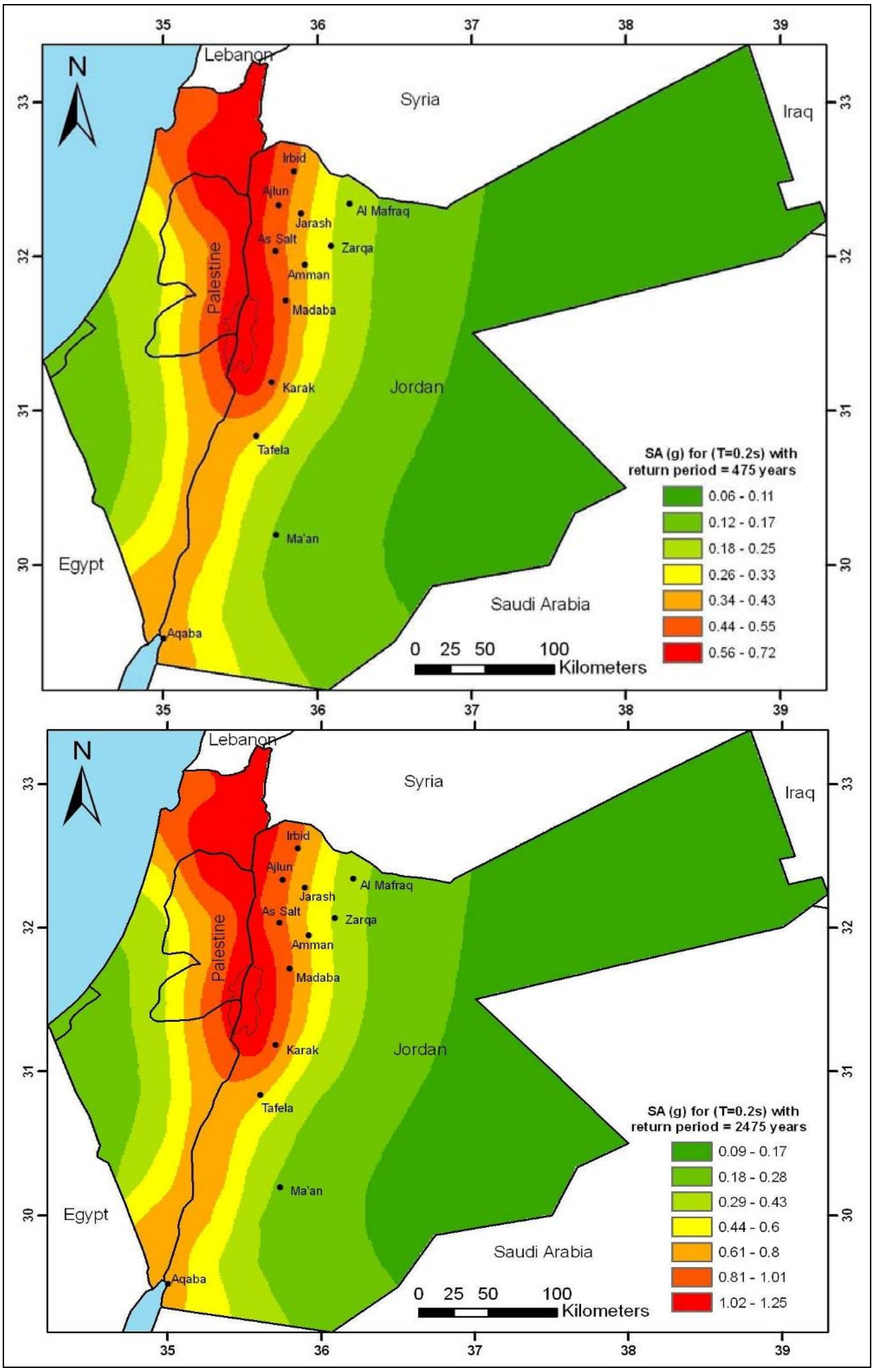

Figure (5): Probabilistic seismic hazard map for spectral acceleration (T=0.2 sec.) at 10% (upper) and 2% (lower) probability of exceedance in 50 years on firm-rock site conditions.

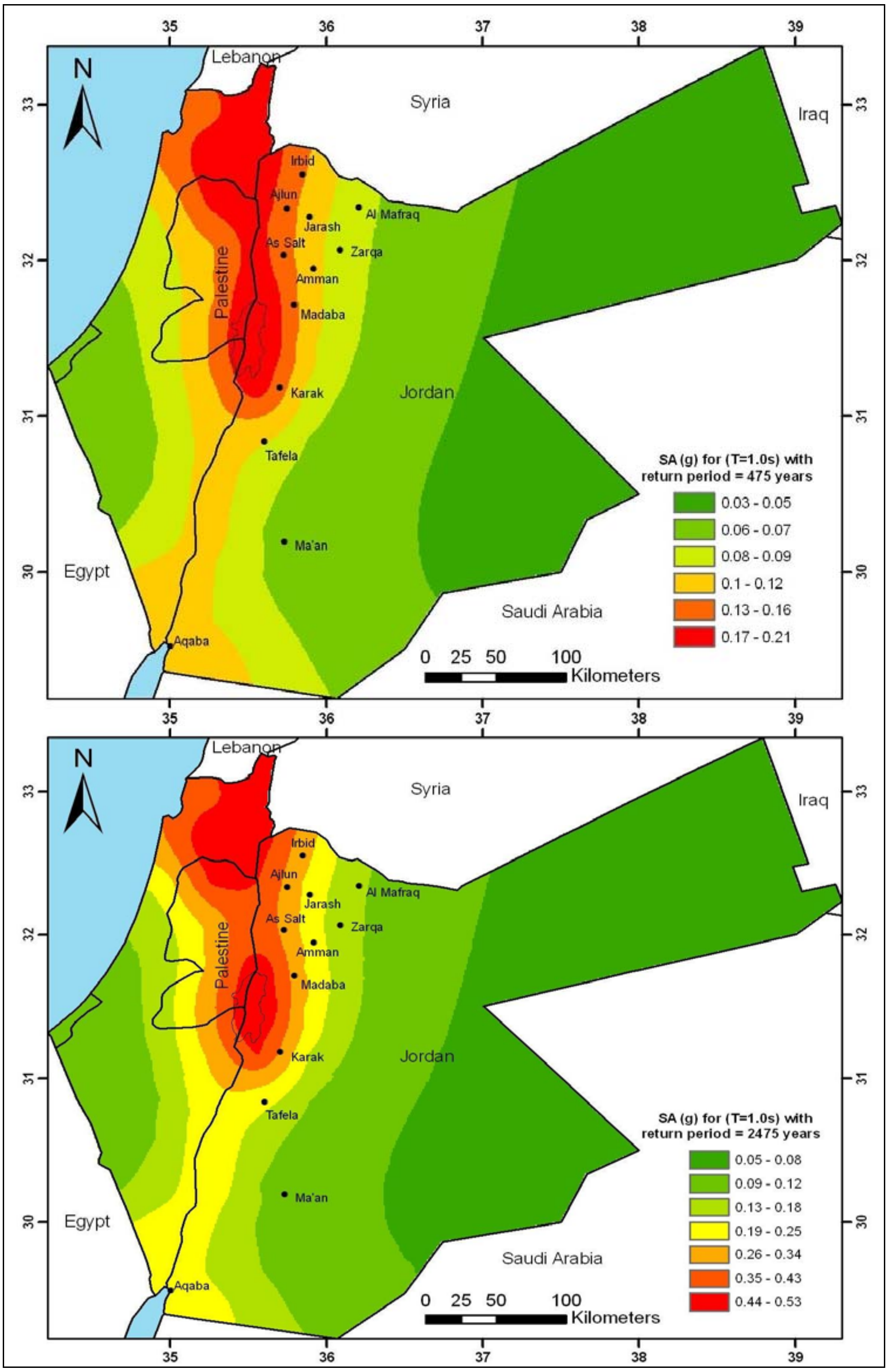

Figure (6): Probabilistic seismic hazard map for spectral acceleration (T=1.0 sec.) at 10% (upper) and 2% (lower) probability of exceedance in 50 years on firm-rock site conditions.

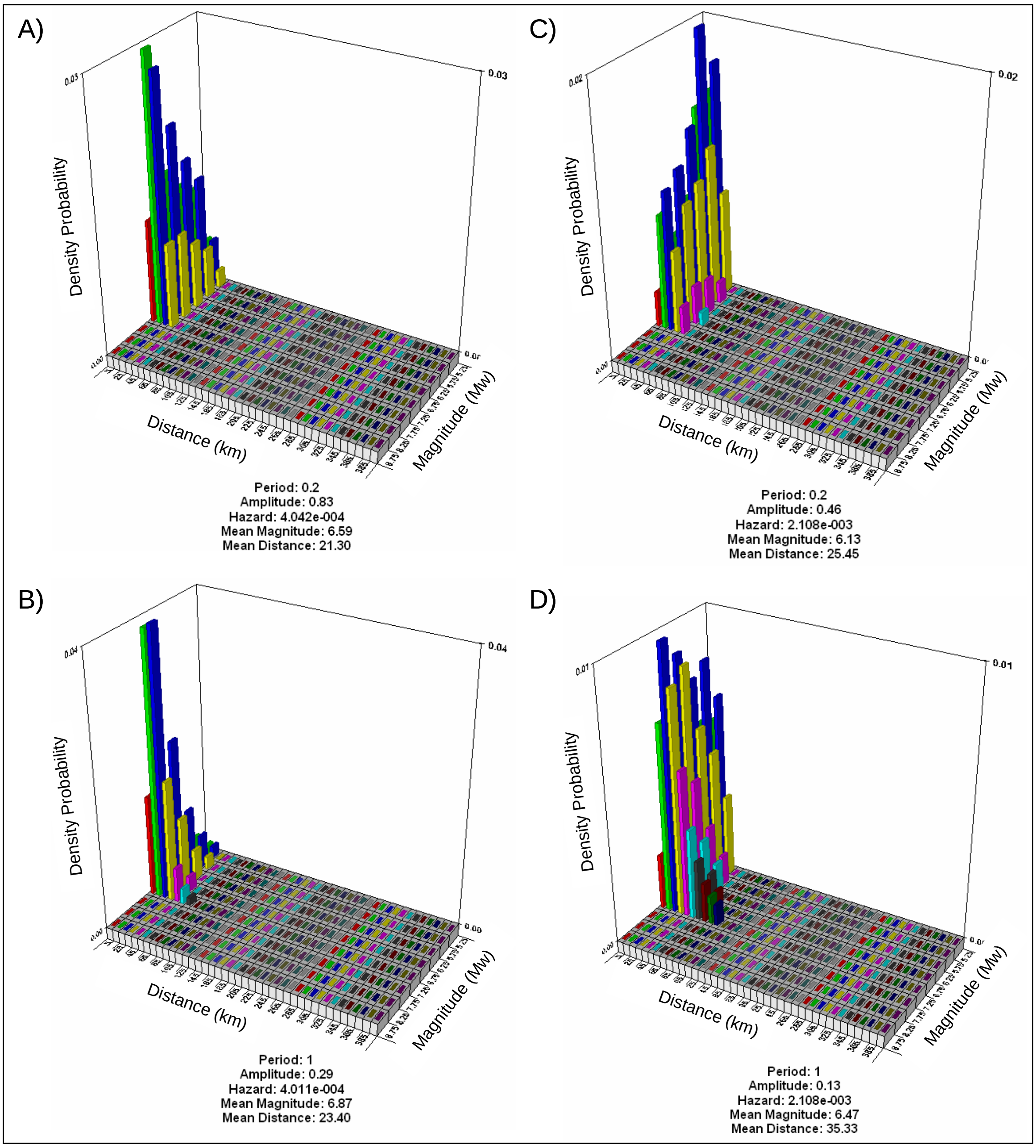

Figure (7): Deaggregation of SA (0.2 sec.) (A) and (1.0 sec.) (B) for the city of Irbid at 2%, and SA (0.2 sec.) (C) and (1.0 sec.) (D) (1.0 sec.) at 10% probability of exceedance.

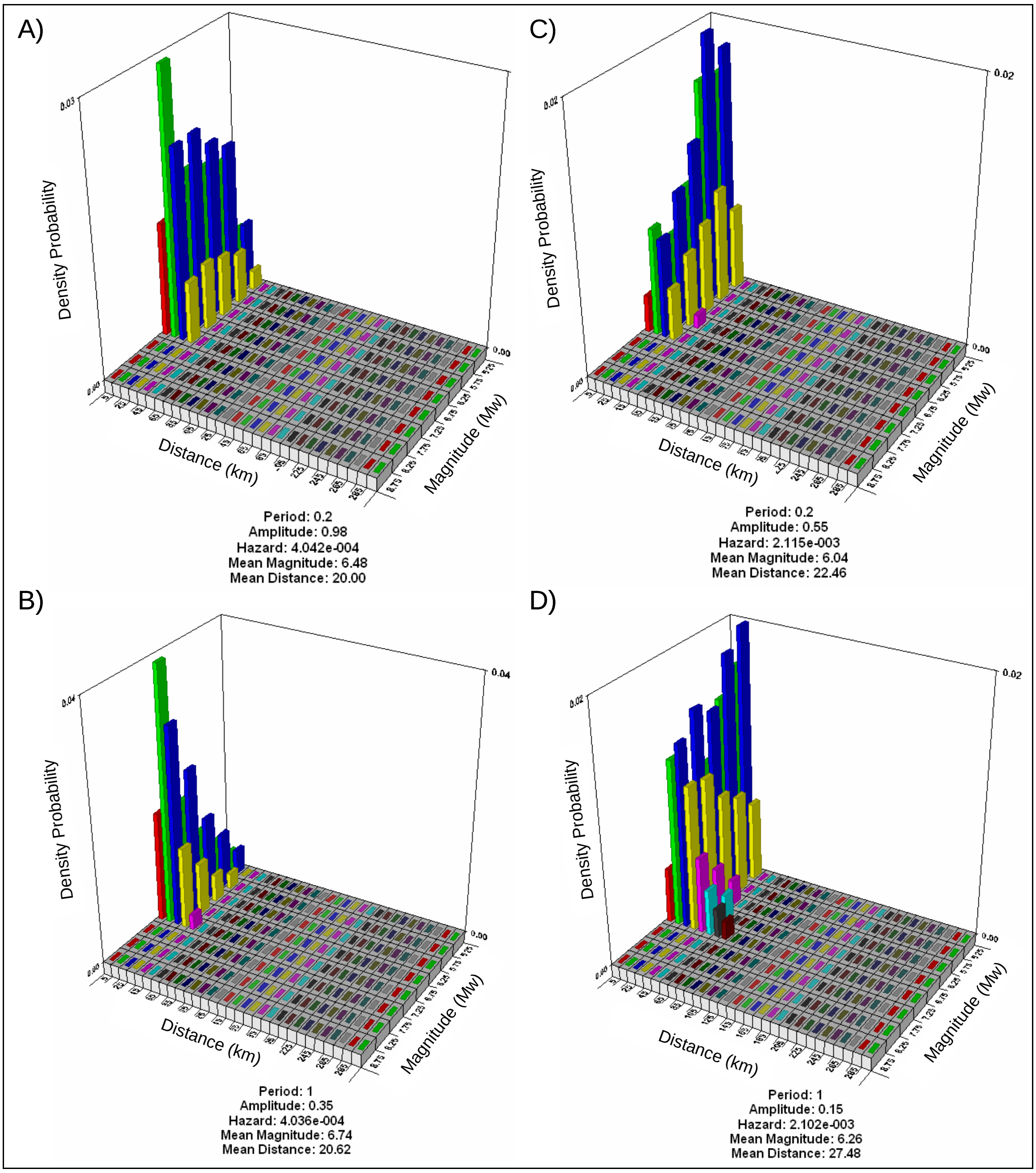

Figure (8): Deaggregation of PSHA results of the city of Ajlun for SA (0.2 sec.) (A) and (1.0 sec.) (B) at 2%, and SA (0.2 sec.) (C) and (1.0 sec.) (D) at 10% probability of exceedance: A typical pattern for the first group.

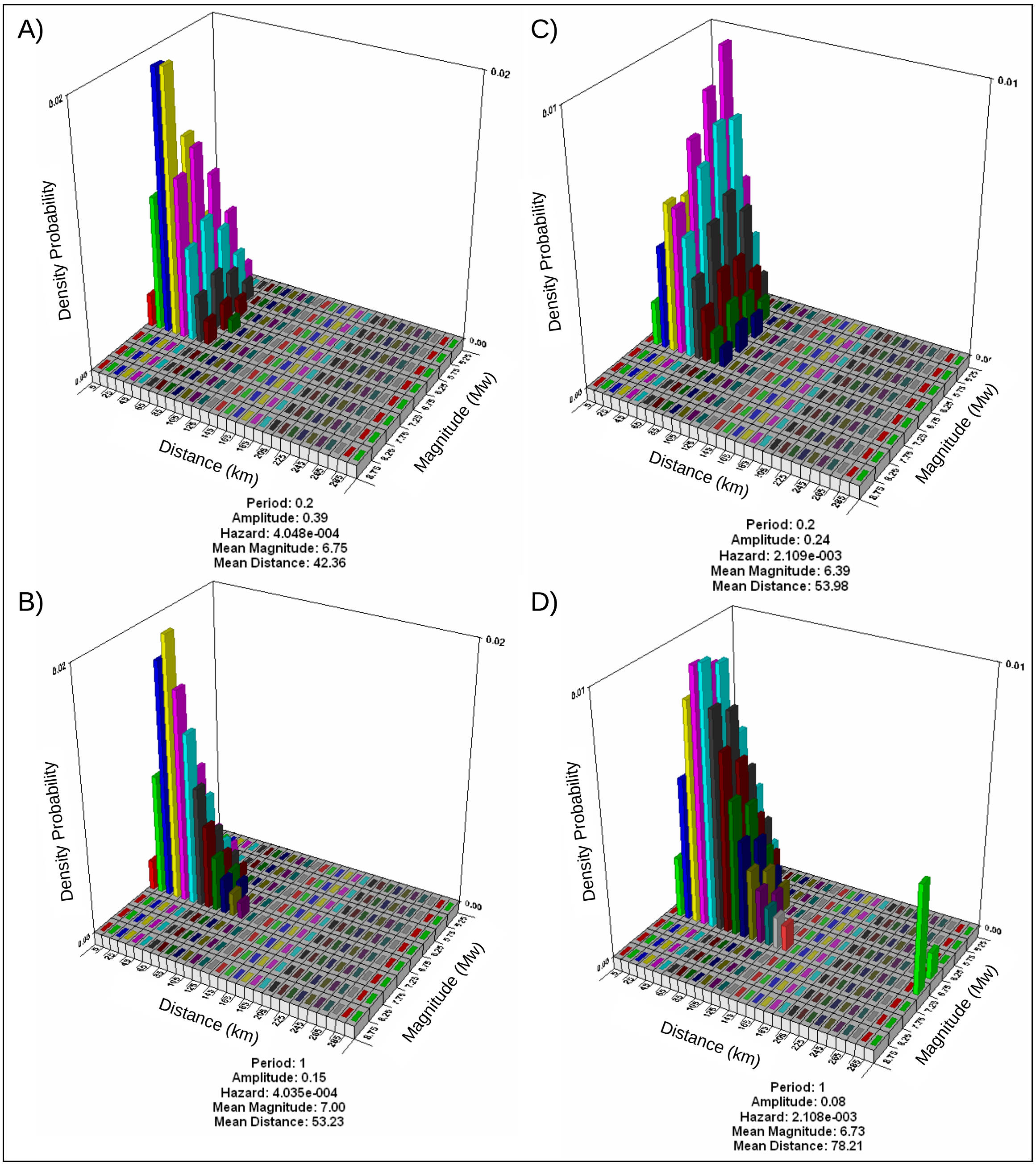

Figure (9): Deaggregation of PSHA results of the city of Zarqa for SA (0.2 sec.) (A) and (1.0 sec.) (B) at 2%, and SA (0.2 sec.) (C) and (1.0 sec.) (D) at 10% probability of exceedance: A typical pattern for the second group.

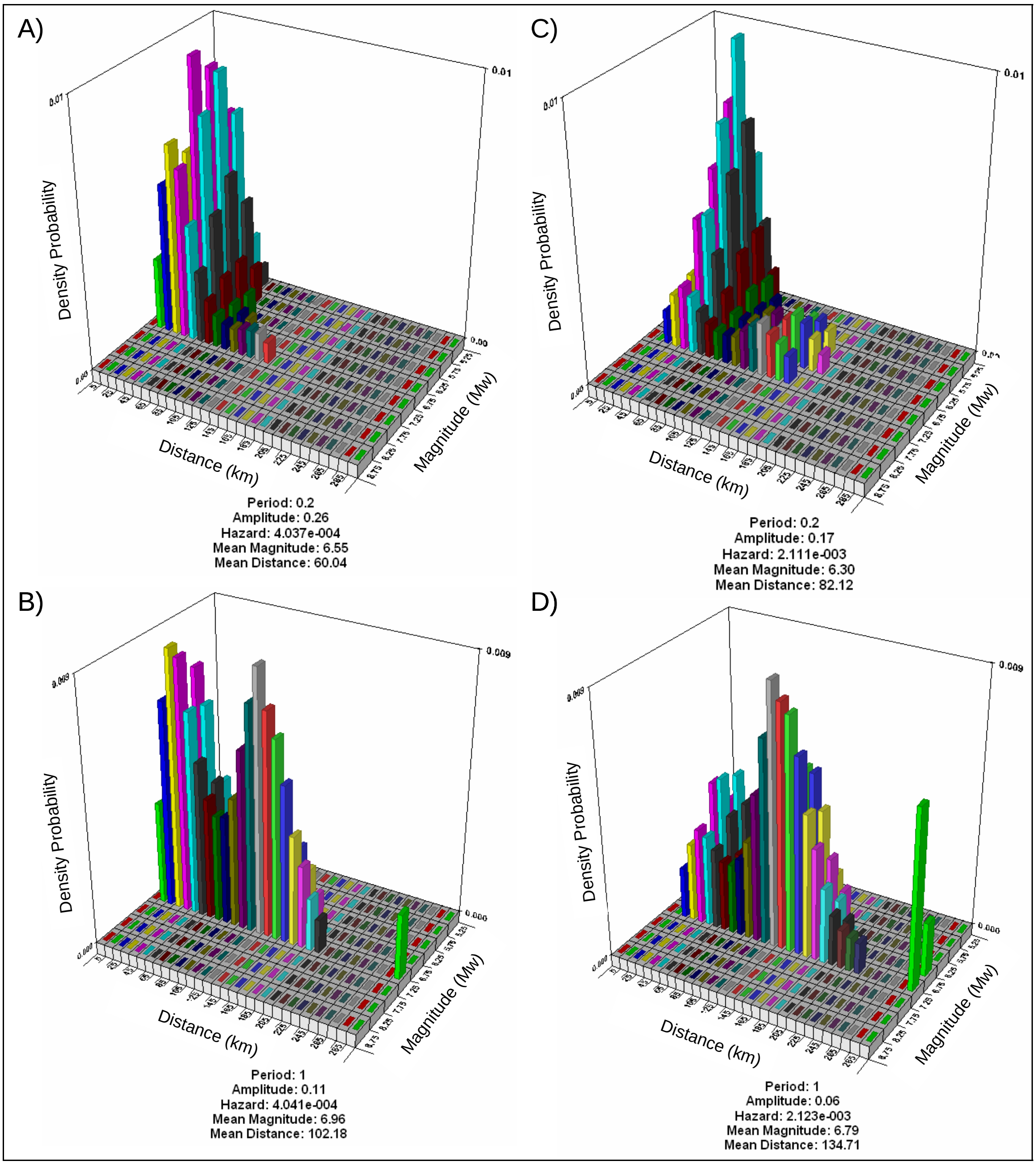

Figure (10): Deaggregation of PSHA results of the city of Ma'an for SA (0.2 sec.) (A) and (1.0 sec.) (B) at 2%, and SA (0.2 sec.) (C) and (1.0 sec.) (D) at 10% probability of exceedance.

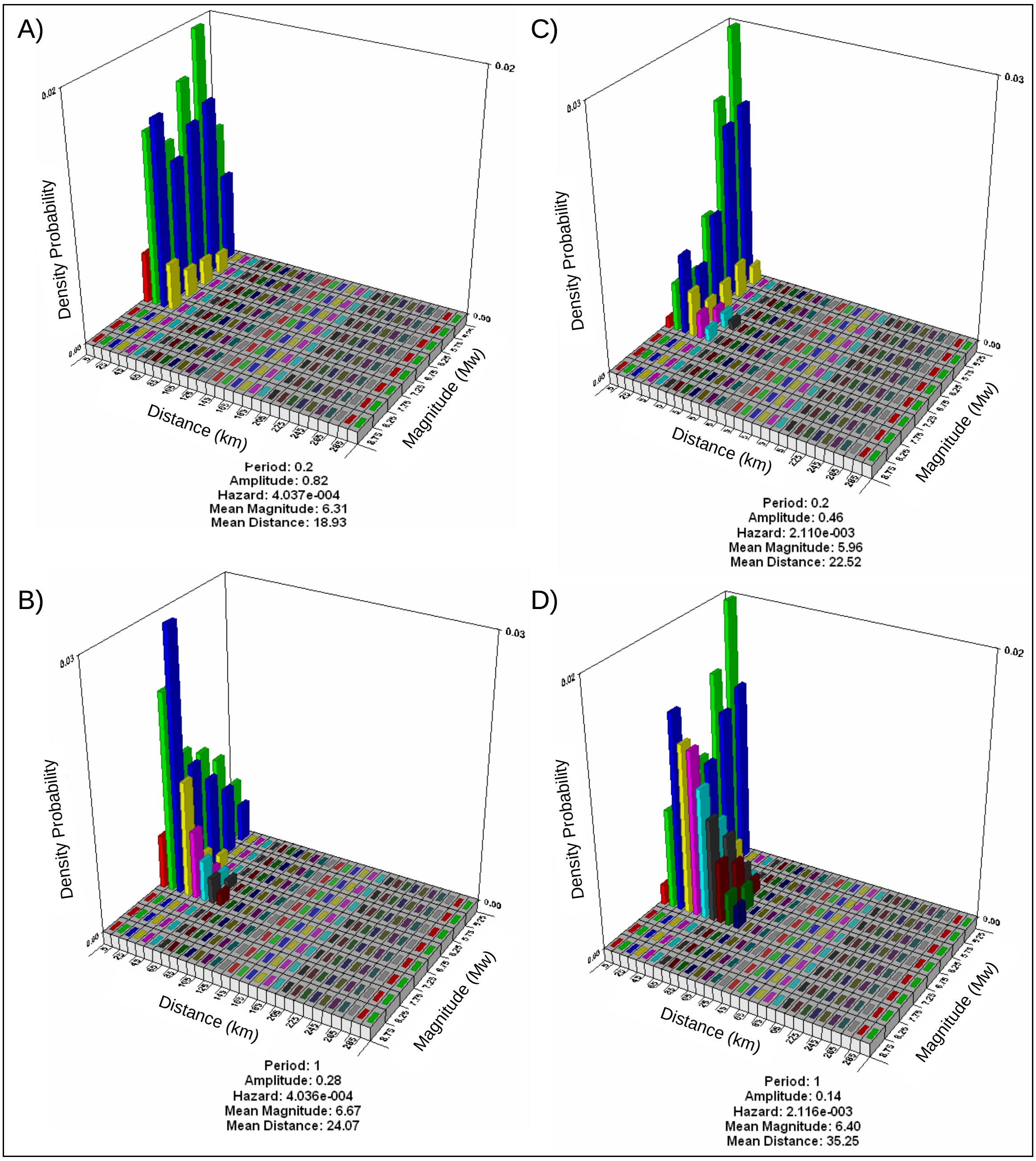

Figure (11): Deaggregation of PSHA results of the city of Aqaba for SA (0.2 sec.) (A) and (1.0 sec.) (B) at 2%, and SA (0.2 sec.) (C) and (1.0 sec.) (D) at 10% probability of exceedance.

such as the Mediterranean and Cyprus sources. Accordingly, resemblance between the cities of the first group (Tables 2 and 3) is mainly attributed to the fact that these cities are located at almost the same distance relative to one or more juxtaposing seismic source areas along the DST fault system (Figure 2). These mean distances indicate that the ground motions of the cities of Ajlun, As-Salt, Irbid, Jarash and Amman are mainly controlled by the Jordan Valley. Meanwhile, the hazard in Madaba and Al-Karak is dominated by the Dead Sea, and for the city of Tafela, it is mainly dominated by the seismicity of Wadi Araba. Table 5 gives a summary of the expected seismic sources of the expected ground motions dominating the selected Jordanian cities.

The cities of the second group are relatively distant from the DST, in comparison to those of the first group. Similarly, the mean distance for the controlling earthquake on the cities of this group is ranging between 42 and 53 km for SA (0.2 sec.) at 2%, while it ranges between 54 and 65 km at 10% probability of exceedance. For SA (T=1.0 sec.), the mean distance for the controlling events are ranging between 53 and 67 km for 2% probability, and between 78 and 92 km for 10% probability of exceedance in 50 years. At larger periods, these cities show a slight tailing towards events located at larger distances. However, this behavior is not extending further than 115-145 km at SA (T=1 sec.) of 2% and 10% probability of exceedance in 50 years (Figure 9-B and Figure 9-D). As indicated from the deaggregation of longer periods, the seismic hazard of these cities is mainly controlled by the Jordan Valley, in addition to some minor contributions from adjacent sources located within the DST, such as Roam, Palmiride and Karmel-Wadi Far'a (Table 5).

The rest of the cities (Ma'an and Aqaba) have dissimilar magnitude-distance deaggregation results. The city of Ma'an has a very distinctive behavior, where very pronounced tailing trends are seen towards higher magnitudes and distant sources (Figure 11). The short period SA (0.2 sec.) is controlled largely by Wadi Araba, with a mean distance of 45km; while the long period is dominated by shaking from Wadi Araba, Dead Sea and Aqaba I, with a tailing distance of ~185 km (Figure 10-B and Figure 10-D). Finally, the city of Aqaba reflects a very unique and focused pattern that is associated with very near distances. Tailing towards lower magnitudes and lower distances is shown, which indicates that hazard within Aqaba is mainly controlled by very frequent near seismic sources (Table 5). Similarly, both long and short periods of the 2 investigated probability levels of exceedance show the importance of the near sources rather than that of the distant sources.

The modal (most probable) magnitude (Mw) for earthquakes that dominates the hazard is equal to 7.25. However, short periods of ground motions have a modal magnitude of 5.25-5.75 at 10% of exceedance. The mean magnitude values show slight variation between the various cities for the investigated ground motions (Tables 3 and 4). The mean magnitude range for the PGA is between 5.7 and 6.2, with an average of 5.9 at 10% probability of exceedance; while for the 2% it ranges between 6.0-6.6. The SA (0.2 sec.) ranges between 6 and 6.4 for 10 % and from 6.3 to 6.8 for 2% probability of exceedance, while the SA (1.0 sec.) ranges between 6.7 and 7 for 2% and between 6.3 and 6.8 for 10% probability of exceedance.

The modal distance distribution indicates the most probable distance to the earthquake controlling the hazard for each city (Tables 3 and 4). The results indicate that for most cities; shaking along faults associated with near seismic area source causes the highest hazard. For SA (0.2 and 1.0 sec.) at 2% probability level; the Aqaba city is mostly dominated by a source located 15 km from the investigated location. Meanwhile, most of the other cities are dominated by sources located at a distance of 25 km which increases up to 35 km for Zarqa and to 45 km for Al-Mafraq and Ma'an. On the other hand, model distances for 10% probability show a slight increase. However, these distances still indicate sources located within the DST region.

Table 4 shows the relative contribution of hazard for each city from the existing seismic sources for the investigated ground motions which strongly suggest that the hazard in these cities is most probably controlled by close sources of relative higher magnitudes. These conclusions are very comparable to the speculations of Malkawi et al. (1995) and Fahmi et al. (1996) who pointed out that the main source of seismic hazard in Jordan is locally attributed to the DST, while other outside sources have little effect on the country.

CONCLUSIONS

We have deaggregated the hazard model of a probability of exceedance for 2% and 10% exceedance probability in 50 years to determine the magnitude and distance of the earthquakes that contribute most to the hazard at specific cities in Jordan. The deaggregation process compares the probabilities of exceeding a certain ground motion level from each event used to characterize the events that contribute most to the hazard for each city. This should allow civil engineers, geologists, seismologists and municipal policy makers to identify the predominant hazardous earthquakes in any region and provide guidance for using representative strong motion records or scenario earthquakes in their design, planning and risk mitigation.

The results indicate that very near seismic sources of relative higher magnitudes are the dominating sources of hazard for the selected Jordanian cities, where the most probable earthquake is equal to 5.25-5.75 for SA (T=0.2 sec.) and 7.25 for SA (T=1 sec.) for a probability of exceedance in 50 years. The contributions from distant sources, such as the eastern Mediterranean, Cyprus and Suez are relatively low, but can not be neglected due to the intrinsic uncertainties and incomplete seismic catalogues.

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