UPGRADING THE SEISMIC HAZARD OF LEBANON IN LIGHT OF THE RECENT DISCOVERY OF THE OFFSHORE THRUST FAULT SYSTEM

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ABSTRACT

This paper presents the results of a study undertaken to evaluate the implications of the newly mapped offshore thrust fault system on the seismic hazard of Lebanon and the already established seismic zone parameters used by the engineering community for earthquake design in Lebanon. This is particularly critical since the fault is located at a close proximity to the major cities and economic centers of the country. The updated seismic hazard was assessed using probabilistic methods of hazard analysis. The potential sources of seismic activities that affect Lebanon were identified, taking into account the newly mapped fault system, and the earthquake recurrence relationships of these sources were developed from instrumental seismology data, historical records, and earlier studies undertaken to evaluate the seismic hazard of neighboring countries. Maps of peak ground acceleration contours, based on 10 percent probability of exceedance in 50 years, and 100 years time spans, were developed.

Keywords: earthquake engineering, ground acceleration, hazard analysis, seismic hazard, seismic zoning, Lebanon

INTRODUCTION AND TECTONIC SETTING OF LEBANON

Historical records document strong earthquakes which have struck Lebanon and its surroundings since 2150 BC, causing wide scale destruction and high death tolls. Within Lebanon itself three earthquakes stand out in its seismic history. On 9 July AD 551 Lebanon was struck by an earthquake with an inferred moment magnitude M_w of around 7.5, followed by a tsunami (*e.g.* Elias *et al*., 2007). The earthquake of 20 May AD 1202 caused severe damage and destruction between the Lebanese coast and western Syria, and was estimated to have an equivalent moment magnitude M_w of around 7.5 (Daëron *et al.*, 2005; Elias *et al*., 2007). The year AD 1759 witnessed two significant seismic events on 30 October and 25 November. The equivalent moment magnitudes M_w of these events were approximately 6.7 and 7.4, respectively (Daëron *et al*., 2005).

In more recent times there have been several sizable earthquakes that struck Lebanon, namely those of 29 September 1918 ($M_w \approx 6.8$) (Plassard & Kogoj, 1981; Harajli *et al.*, 1994), 16 March 1956 (double shock, $M_w \approx 6.3$ and 6.1) (Khair *et al.*, 2000), and 21 March 1997 (two events, M ≈ 5.6 and 5) (Khair *et al.*, 2000). Early in 2008 part of South Lebanon was shaken by a series of earthquakes, of which the largest was of a reported magnitude of 5.1 on 15 February (European-Mediterranean Seismological Centre).

The seismic history of Lebanon is not surprising, given that the country lies along the 1000-km-long left-lateral Levant fault system (LFS). This fault system extends from the seafloor spreading in the Red Sea to the Taurus mountains in southern Turkey, and thus forms the plate boundary between the Arabian plate and the Sinai-Levantine block. This fault system is responsible for a significant amount of seismic events in the eastern Mediterranean.

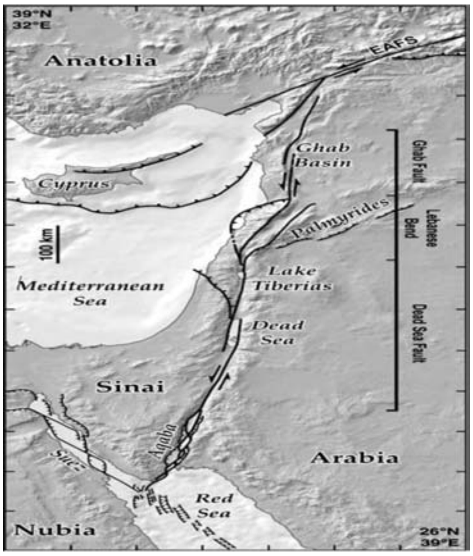


Figure 1. Map of the Levant fault system; EAFS – East Anatolian fault system (source: (Daëron, 2005)).

The southern segment of the LFS extends from the Gulf of Aqaba to the Hula depression in south Lebanon. This segment, also known as the Dead Sea fault (DSF), has a fairly simple geometry and strikes in an approximate N-S direction. Upon entering Lebanon however it branches into a more complex system of braided faults (Walley, 1988), also known as the Lebanese Restraining Bend (LRB). When exiting Lebanon in the North the LFS resumes its N-S direction as the Ghab fault. In southern Turkey the LFS meets the East Anatolian fault system (Figure 1).

Figure 2 shows the main faults within Lebanon, as well as many smaller and shallower faults that cover the country's surface. Until relatively recently the main active faults within the LRB were thought to be the Yammouneh, Rachaya, Serghaya and Roum faults. Lately, however, the SHALIMAR marine geophysical campaign proved the existence of a previously unknown, active thrust fault system – the Mount Lebanon thrust (MLT) (Briais *et al*., 2004). This newly identified, ~150 km long, east-dipping, crustal thrust, plunges under the western flanks of the Mount Lebanon range. Its surface trace lies mainly offshore, between Tripoli in the North and Saida in the South, cutting the seabed at not more than 8 km from the coast of central Lebanon between Beirut and Anfeh (Elias *et al*., 2007). Elias *et al.* (2007) demonstrated that the disastrous, $M_w \approx 7.5$, tsunamigenic, AD 551 earthquake that destroyed most of the coastal cities of Lebanon occurred on the Mount Lebanon thrust system, and suggested that the recurrence period for similar earthquakes on this fault is between 1500 and 1750 years. One of the smaller faults is the Zrariye-Chabriha fault, which was initially thought to be the source of the series of earthquakes early 2008, including the M = 5.1 event on February 15. At present very little is known regarding the geology and seismic history of this fault. But according to Elias (2006), the Zrariye-Chabriha fault is a thrust fault. The fault is approximately 26 km in length, and runs from just North of Tyre in a NEE-SWW direction inland.

The geometry of the LRB is illustrated in Fig. 3 which shows two vertical cross-sections of the faults, the locations of which are indicated by the two dashed lines (labeled 1-1 and 2-2) inFigure 2. Elias (2006) suggests that the Mount Lebanon Thrust connects to the Yammouneh fault in the South and North of Lebanon. The southern connection has not yet been traced, but for the purpose of this study it was assumed as indicated in Fig. 2 by the dashed line. The northern connection consists most likely of the Tripoli and Akkar thrusts. These connections might have been involved in ruptures along the thrust, and might as well be in the future. Figs. 2 and 3 clearly demonstrate that a significant part of the coastal area lies right above the Mount Lebanon thrust. The thrust has an upper dip angle of 40º and a lower of 25º with respect to the horizontal plane and cuts at a depth of up to ~8 km underneath the coastline between Tripoli and Saida (as estimated from a more detailed cross-section of Mount Lebanon presented by Elias (2006)).

Given the location of Lebanon on the seismic map, several studies have been undertaken for evaluating and re-evaluating the seismic hazard of this country (Harajli *et al*., 1994; Mokaddem, 1994; Asbahan, 2001; Harajli *et al*., 2002; Elnashai & El-Khoury, 2004). Also, because of the importance of earthquake activity in the Eastern Mediterranean and the potential associated danger, several research efforts have attempted to assess the seismic hazard of neighboring countries (BenMenahem & Aboodi, 1981; Yücemen, 1992; Al-Haddad *et al*., 1994; Malkawi *et al*., 1995; Al-Tarazi, 1999; Yilmaztürk & Burton, 1999; El-Hefnawy *et al*., 2006; Shapira *et al*., 2007; Cagnan & Tanircan, 2010).

OBJECTIVE OF THE STUDY

As indicated earlier, until recently the main active faults within the LRB were thought to be the Yammouneh, Rachaya, Serghaya and Roum faults. Accordingly, all earlier studies of the seismic hazard of Lebanon were based in part on this assumption. The recent mapping by SHALIMAR marine geophysical campaign of a previously unknown, active thrust fault system – the Mount Lebanon thrust (MLT) – calls for re-evaluation of the seismic hazard of Lebanon, particularly since the newly mapped fault cuts right underneath and along the coastal area where most of Lebanon's population, cities and capital investments are concentrated.

The objective of the current study is to update the seismic hazard of Lebanon, taking into account the newly mapped fault system and associated geological and seismological findings, and recently developed ground motion attenuation relationships appropriate to the region under investigation.

A brief description of the hazard analysis method used in this study is provided in the following section.

Figure 2. Faults within Lebanon: AT – Aakkar thrust; DSF – Dead Sea fault; GhF – Ghab fault; MLT – Mt. Lebanon thrust; NT – Niha thrust; RaF – Rachaya fault; RF – Roum fault; SF – Serghaya fault; TT – Tripoli thrust; YF – Yammouneh fault; ZCF – Zrariye-Chabriha fault (after Elias *et al.*, (2007)).

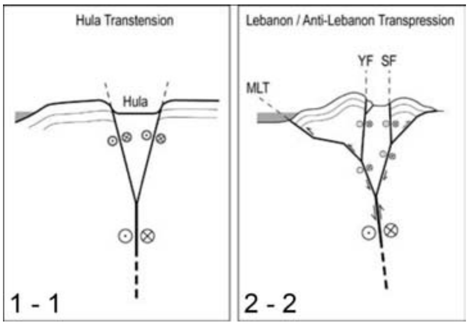


Figure 3. Vertical cross-sections of the LRB showing the inferred geometries of the Dead Sea and Rachaya faults in section 1-1 and the Mount Lebanon thrust, Yammouneh and Serghaya faults in section 2-2; the locations of the sections are shown in Figure 2. The arrows and circles indicate the direction of the plate movement (source: (Daëron 2005)).

METHOD OF SEISMIC HAZARD ANALYSIS

The seismic hazard was evaluated using probabilistic methods of hazard analysis based on the standard seismic hazard analysis methodology introduced by Cornell (1968) and McGuire (1978). An upgraded version of the computer software EZ-FRISK^{TM} developed by Risk engineering, Inc. was used to perform the analysis, which has the capability of handling combinations of seismic sources of different types and multiple attenuation equations, and to perform multi-site analyses.

A catalogue of the seismic activity inside Lebanon and its vicinity was compiled from instrumental seismology data and historical records. The potential sources of seismic activities that affect the hazard in Lebanon were identified, along with the newly discovered tectonic feature (offshore thrust system). The earthquake recurrence relationships of these sources were developed in accordance with the Gutenberg-Richter law from the earthquake catalogue, geological studies, and earlier studies undertaken to evaluate the seismic hazard of nearby countries. Also, a ground motion attenuation relationship relevant to the region under investigation was selected.

The Gutenberg-Richter recurrence law (Gutenberg & Richter, 1956) is expressed as follows:

$$Log(N \geq m) = a - bm \tag{1}$$

where m is the earthquake magnitude and N is the number of earthquakes with magnitude $\geq m$ per annum. Equation (1) can be re-written as:

$$N(m) = e^{\alpha - \beta m} \tag{2}$$

where $\alpha = a \ln 10$, and $\beta = b \ln 10$. For engineering applications, the effect of earthquakes of magnitude less than a minimum value (m_o) on the experienced structural and nonstructural damage through ground shaking is likely to be insignificant. Therefore, by eliminating the range of magnitudes of m_o and smaller, equation (2) can be rewritten as:

$$N(m) = ve^{-\beta(m - m_o)} \tag{3}$$

where: $$v = e^{\alpha - \beta m_o} \tag{3a}$$

It was assumed that the attenuation characteristics of the ground motion are isotropic, that is, they are independent of the location of the site relative to the source of energy release.

The sensitivity of the results to different assumptions regarding the seismic sources in the Lebanese segment and choice of the attenuation relationship was evaluated. The hazard results are presented in maps of contour lines of peak ground acceleration for a 10% probability of exceedance in 50 years and 100 years exposure time, respectively.

EARTHQUAKE CATALOGUE

The earthquake catalogue consists of instrumental seismic data (European-Mediterranean Seismological Centre; U.S. Geological Survey) as well as historical earthquake data pertaining to the seismic activity inside Lebanon and vicinity (Plassard & Kogoj, 1981; Ambraseys & Melville, 1988; Harajli *et al.*, 1994; Mokaddem, 1994; Khair *et al.*, 2000; Gomez *et al.*, 2003; Daëron, 2005; Daëron *et al.*, 2007; Elias *et al.*, 2007). A catalogue of historical and instrumental seismic records in this part of the world, going back to BC 1365, had already been presented by Harajli *et al.* (1994). This catalogue has been further completed and expanded to cover the periods 2150 BC to AD 1896 for historical records and 1903 to 2009 for instrumental records. The complete catalogue is reported elsewhere (Huijer *et al.*, 2010).

A summary of the major historical seismic events with magnitude $M \geq 6$ that occurred between 2150 BC and AD 1837 along the Ghab fault, Dead Sea fault and Lebanese Restraining Bend is provided in Fig. 4. The instrumented seismic events between 1903 and 1997 with $M \geq 3$ are shown in Figure 5. Although earthquake magnitudes less than 3.0 do not have any significant effect on the hazard analysis, instrumental events with $M \geq 2$ for the period 1998 to 2009 are presented in Fig. 6 to give an idea about the concentration of seismic activity within Lebanon.

SEISMIC SOURCES AND EARTHQUAKE RECURRENCE RELATIONSHIP

Since the seismic hazard evaluation of Lebanon is mainly influenced by the seismic activity within the country or at a close proximity to it, an effort has been made to define the seismic sources and establish the earthquake recurrence relationship in the Lebanese segment (LRB). Particular attention has been given to the newly discovered tectonic feature offshore Lebanon (Mount Lebanon thrust) and for modelling the earthquake recurrence of this seismic source. In addition to a region defined as the Lebanon region, several neighbouring and potentially contributing sources have been considered. The surrounding seismic sources as well as those that make up the LRB are described next.

Surrounding seismic sources

Several neighboring seismic sources (Figure 7) may affect the seismic hazard of Lebanon:

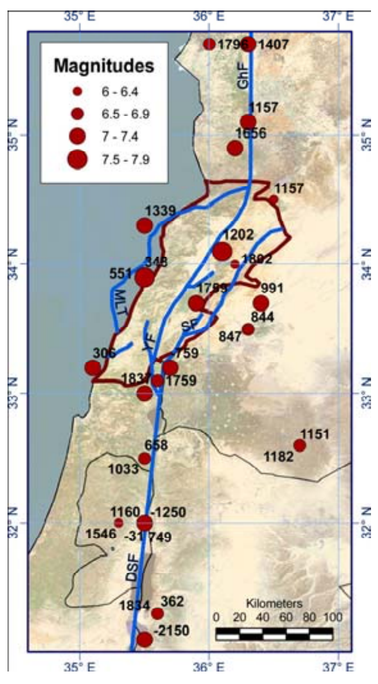
Dead Sea fault: A strike-slip type of fault modelled as a line source, extending from the southern part of the Dead Sea to the southern Lebanese border in a S-N direction, with a total length of about 257 km.

Ghab fault: Also a strike-slip type of fault modelled as a line source, extending from the northern Lebanese border into the North of Syria in a S-N direction, with a total length of about 124 km.

Karasu: An area source to the North of the Ghab fault, with a total area of about 29,000 km^2. It mainly includes seismic events along part of the East Anatolian fault system in southern Turkey.

Syria region: An area source to the East of Lebanon, with a total area of about 4300 km^2. It accounts for a cluster of instrumentally recorded seismic activity in that area.

Cyprus region: Modelled as an area source, with an approximate area of 70,000 km^2. It includes seismic activity in and around Cyprus.



Year	Month	Day	Lat.	Long.	M_w	Zone
-2150	-	-	31.1	35.5	7.3	Jordan
-1250	-	-	32.0	35.5	6.8	Jordan
-854	-	-	-	-	6.9	Jordan
-759	10	11	33.2	35.7	7.3	Jordan
-590	-	-	-	-	6.8	Lebanon
-140	-	-	-	-	7.0	Lebanon
-31	9	2	32.0	35.5	7.0	Jordan
19	-	-	-	-	6.8	Lebanon
130	-	-	-	-	6.3	Lebanon
306	-	-	33.2	35.1	7.1	Lebanon
348	-	-	33.9	35.5	7.0	Lebanon
362	5	24	31.3	35.6	6.7	Jordan
525	-	-	-	-	6.7	Lebanon
551	7	6	33.9	35.5	7.5	Lebanon
658	6	15	32.5	35.5	6.9	Jordan
749	1	18	32.0	35.5	7.3	Jordan
844	9	18	33.5	36.3	6.8	Lebanon
847	4	-	33.5	36.3	6.4	Lebanon
991	4	5	33.7	36.4	7.2	Lebanon
1033	12	5	32.5	35.5	6.7	Jordan
1063	4	20	-	-	7.1	Lebanon
1151	9	28	32.6	36.7	6.4	Jordan
1157	7	15	34.5	36.5	6.3	Lebanon
1157	8	15	35.1	36.3	7.3	Ghab
1160	-	-	32.0	35.3	6.3	Jordan
1170	-	-	-	-	7.5	Ghab
1182	-	-	32.6	36.7	6.7	Jordan
1202	5	20	34.1	36.1	7.5	Lebanon
1339	-	-	34.3	35.5	7.1	Lebanon
1407	4	29	35.7	36.3	7.1	Ghab
1546	1	14	32.0	35.3	7.0	Jordan
1656	2	-	34.9	36.2	7.0	Ghab
1759	10	30	33.1	35.6	6.7	Jordan
1759	11	25	33.7	35.9	7.4	Lebanon
1796	4	26	35.7	36.0	6.7	Ghab
1802	-	-	34.0	36.2	6.4	Lebanon
1834	5	23	31.3	35.6	6.5	Jordan
1837	1	1	33.0	35.5	7.1	Jordan

Figure 4. Large historical earthquakes along the Dead Sea transform fault between 2150 BC and AD 1837 with $M \geq 6$.

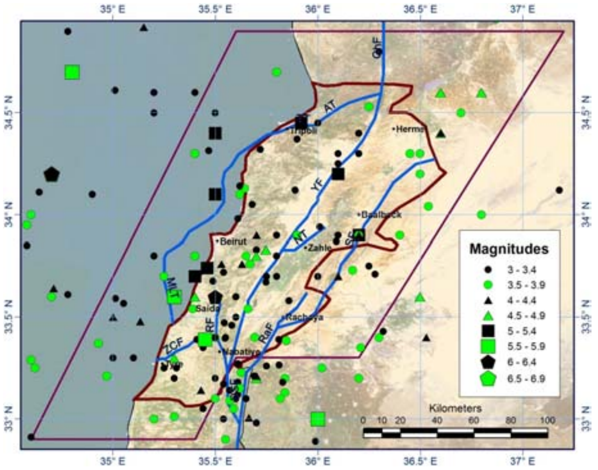


Figure 5. Instrumented earthquake events in and around Lebanon between 1903 and 1997 with $M \geq 3$.

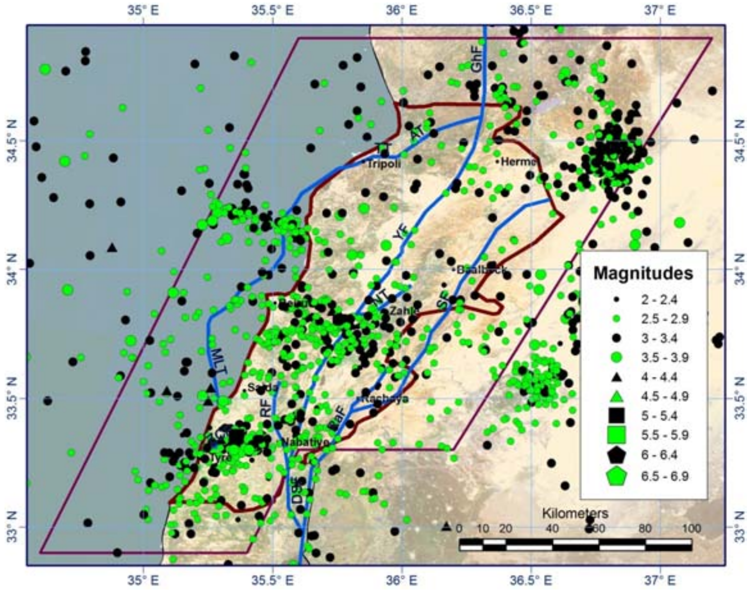


Figure 6. Instrumented earthquake events in and around Lebanon between 1998 and 2009 with $M \geq 2$, retrieved from the EMSC Euro-Med Bulletin.

The Gutenberg-Richter parameters a and b ($[Log(N \geq M) = a - bM]$, where N is number of earthquakes per annum with magnitude greater than or equal to M) as well as the minimum and maximum earthquake magnitudes ($M_{\min}$ and $M_{\max}$, respectively) for each of these surrounding seismic sources are given in Table 1. The parameters for the Cyprus region area source proposed by El-Hefnawy *et al*. (2006) were used for the purpose of this study. All other Gutenberg-Righter parameters were obtained by means of linear regression, and $M_{\max}$ was obtained from the available seismic records.

TABLE 1

Parameters for Surrounding Seismic Sources

Seismic source	a	b	M_{min}	M_{max}
Dead Sea fault	2.84	0.82	3	7.3
Ghab fault	2.86	0.91	3	6
	-1.43	0.19	6	7.8
Karasu	4.40	1.04	3	6
	1.27	0.52	6	8
Syria region	2.00	0.78	3	4.6
Cyprus region	2.79	0.67	3	7.6

The Lebanon region

Several models were used to describe the seismic sources in the LRB and the implications of each on the seismic hazard results were assessed. Each of these models includes all the above mentioned surrounding seismic sources in neighbouring regions as well as the sources that make up the LRB. In this paper only one model, believed to be most realistic and reasonable, is presented for describing the sources in the Lebanese segment. Other models and corresponding hazard results are presented in detail elsewhere (Huijer *et al.*, 2010).

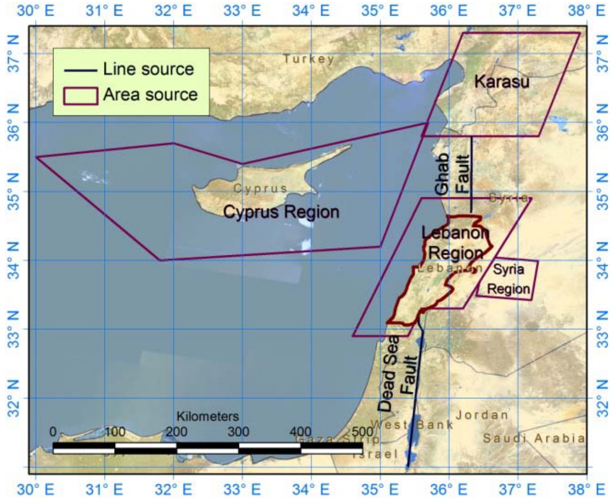


Figure 7. Lebanon with its surrounding seismic sources.

In the model presented in this paper, the Yammouneh fault, the Mount Lebanon thrust as well as the Rachaya, Serghaya and Zrariye-Chabriha faults (Fig. 8) are all assumed to be active faults and all major earthquakes are assigned to these faults. All remaining earthquakes are assigned to the Lebanon region area source as background seismicity, which accounts for the seismic activity on the many other smaller faults.

The dashed lines in Fig. 8 represent the presumed connections of the Mount Lebanon thrust to the Yammouneh fault. These extensions were considered in a separate sub-model, the results of which are presented by Huijer *et al.* (2010).

The Yammouneh fault was modelled as a vertical strike-slip fault and the Mount Lebanon thrust as a reverse fault with an upper dip angle of 40º and a lower of 25º with respect to the horizontal plane. Furthermore, the Rachaya and Serghaya faults were modelled as strike-slip faults and the Zrariye-Chabriha fault as a thrust fault. The return periods of $M_{\max}$ were taken to be 1250, 1750 and 1850 years for the Yammouneh fault, Mount Lebanon thrust and Serghaya fault, respectively. The Gutenberg-Richter parameters a and b as well as the minimum and maximum magnitudes for each of these surrounding seismic sources are given in Table 2.

TABLE 2

Parameters for Seismic Sources

Seismic source	a	b	M_{min}	M_{max}
Mount Lebanon thrust	2.00	0.70	3	7.5
Yammouneh fault	0.23	0.44	3	7.5
Rachaya fault	1.25	0.67	3	6.7
Serghaya fault	0.84	0.55	3	7.4
Zrariye-Chabriha fault	0.54	0.50	3	5.1
Lebanon region (remaining)	3.08	1.01	3	5.0

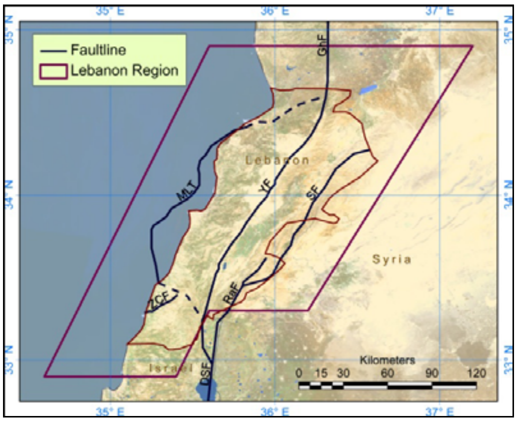


Figure 8. LRB seismic sources for the hazard analysis.

Attenuation relationship

In this study, the next generation attenuation (NGA) equation developed by Idriss (2008) was used for the purpose of hazard analysis. This equation relates the acceleration to the distance from the source of energy release, earthquake magnitude, and source type, and is given as follows:

$$\ln[PSA(T)] = \alpha_1(T) + \alpha_2(T)M - [\beta_1(T) + \beta_2(T)M]\ln(R_{rup} + 10) + \gamma(T)R_{rup} + \varphi(T)F \tag{4}$$

where $PSA(T)$ is the acceleration for period T, at a 5% spectral damping ratio (in g), M is the moment magnitude, R_{rup} is the closest distance to the rupture surface (in km), and F designates the source mechanism (F = 0 for “strike-slip” and F = 1 for “reverse” events).

For the values of the parameters $\alpha_1(T)$, $\alpha_2(T)$, $\beta_1(T)$, $\beta_2(T)$, $\gamma(T)$, and $\varphi(T)$ refer to Idriss (2008).

The parameters for the Idriss equation (2008) have thus far only been developed for sites with an average shear wave velocity in the upper 30 m, $V_{s30} \geq$ 900 m/s, as well as for sites with 450 m/s $\leq V_{s30} \leq$ 900 m/s. Since the main objective of this study is to calculate PGA values at the bedrock, which usually has an average shear wave velocity $V_{ave} >$ 750 m/s (Sadek *et al*., 2004), this limitation poses no obstacle for the subject hazard evaluation. Furthermore, the fact that the attenuation equation (eq. 4) can only be implemented for strike-slip and reverse sources is consistent with the faulting mechanisms present in the models.

A plot of the peak ground acceleration (PGA) attenuation with distance for strike-slip faults and 450 m/s $\leq V_{s30} \leq$ 900 m/s is shown in Fig. 9. The values for reverse faults are slightly higher by 12.7%.

Other attenuation equations were used in order to test the sensitivity of the results to the choice of attenuation relationship. These relationships are discussed in detail elsewhere (Huijer *et al*., 2010).

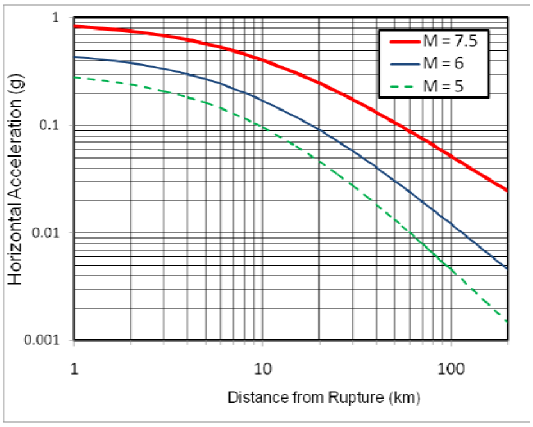


Figure 9. PGA versus R_{rup} for the Idriss 2008 attenuation relationship for strike-slip faults.

RESULTS OF HAZARD ANALYSIS

Lebanon was divided using a 0.1 by 0.1 degree mesh, with a total of 478 different locations of mesh nodal points. For each of these points the peak ground accelerations (PGA) with a 10% probability of being exceeded in 50, 100 and 500 years (return periods of 474.6, 949.1 and 4745.6 years, respectively) were calculated for all models using the seismic hazard analysis software EZ-FRISK^{TM}. Based on the PGA values at these points, contour lines were developed using the GIS software ESRI® ArcMap^{TM}.

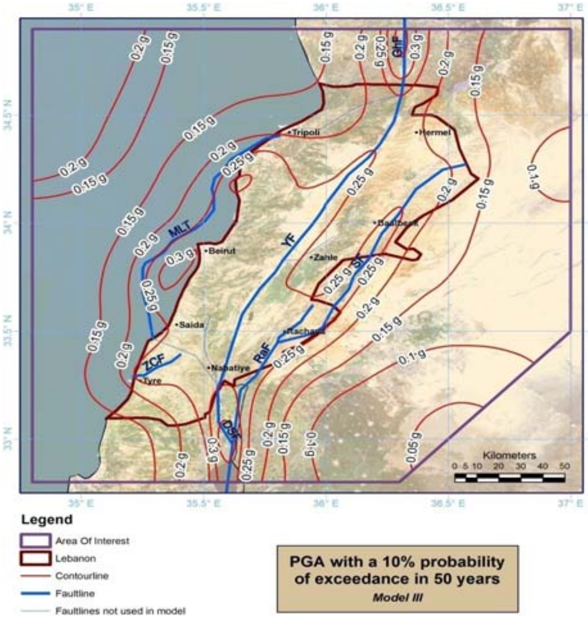


Figure 10. Contour map of PGA with a 10% probability of exceedance in 50 years.

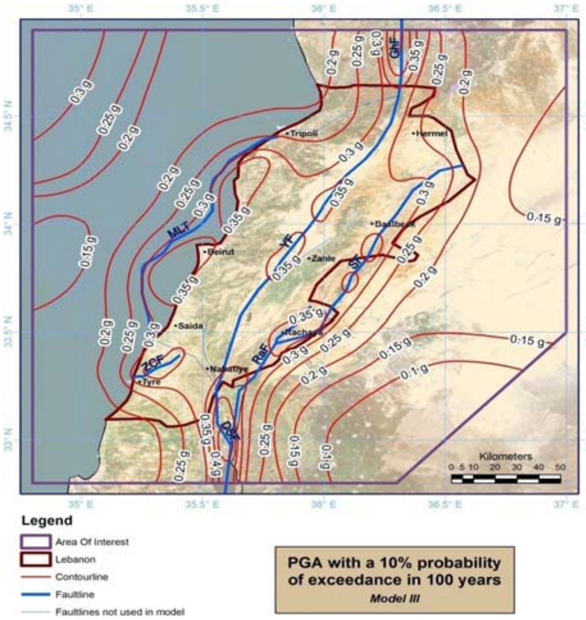


Figure 11. Contour map of PGA with a 10% probability of exceedance in 100 years.

What follows is a brief description of the hazard results for the seismic source model presented in this paper, which is believed to be the most reasonable model for upgrading the seismic hazard in Lebanon. Several additional seismic models were also evaluated, but not shown in this paper for brevity. Detailed description and discussion of the results of these models are presented in Huijer *et al*. (2010).

Peak ground acceleration

Figure 10 and Figure 11 show the contour maps of peak ground acceleration (PGA) corresponding to a 10% probability of exceedance in 50 and 100 years respectively. It can be seen in these Figures that the PGA for a 50 year time span in the Lebanese territories varies between 0.2 g in the eastern part of the country to 0.30 g in the western part near the coastal areas, whereas Harajli *et al.* (2002) established a PGA of 0.15 to 0.25 g in the coastal area and 0.3 to 0.35 g along the Yammouneh fault, and Elnashai and El-Khoury (2004) calculated a PGA of 0.15 to 0.18 g in the coastal area. For a 100 year life span, this PGA increases from a minimum of 0.25 g to about 0.35 g . This clearly indicates that the newly mapped offshore fault system has a great implication on the seismic hazard and its distribution across Lebanon.

Proposed seismic hazard map

In light of this study and the newly discovered offshore tectonic feature, it is recommended to design for a PGA of 0.25 g in the larger part of Lebanon. However, for the coastal area between Saida and Tripoli, where most of Lebanon's population and capital investments are located, as well as for the area around the central part of the Yammouneh fault, it is advisable to adopt a PGA of 0.3 g .

The recommended ground accelerations above are the minimum that should be used in seismic design and may be taken conservatively as the ground acceleration at the bedrock level. The final design acceleration may be amplified depending on the type of soil overlying the bedrock, and the dynamic characteristics of the structure. Classification of soils in Lebanon with regard to their influence on the dynamic response under earthquake loading was covered in detail elsewhere (Harajli *et al*., 1994).

CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

Lebanon is a country of moderate to high seismic hazard. The expected PGA with a 10% probability of exceedance in 50 years varies mostly between 0.20 g and 0.3 g .

The presence of the newly discovered Mount Lebanon thrust does indeed have a significant impact on the earlier established seismic hazard map of Lebanon, especially for the coastal area where more than 70% of the country's population and capital investments concentrate.

The proposed seismic zone parameter for the coastal area between Saida and Tripoli, as well as for the area around the central part of the Yammouneh fault should be increased from its present value of 0.2 g to 0.3 g . The proposed parameter for the remaining part of the country is 0.25 g .

This increase in seismic hazard implies that all civil engineering facilities, including buildings and bridges, that are yet to be constructed in the coastal zone between Saida and Tripoli should be designed using the design and reinforcement detailing requirements (in reinforced concrete structures) of "high seismic hazard" established in international codes of practice.

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