# Seismic Hazard Assessment and Design Requirements for Beirut, Lebanon

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**SUMMARY:**
This paper presents new probabilistic seismic hazard estimates for Beirut, Lebanon. In recent years, new geological data along the Lebanese restraining bend as well as bathymetric mapping of the Mount Lebanon Thrust (MLT) have provided further insights on the tectonic setting and seismic potential of the faults in this region. These recently available data have been used herein as basis for the development of a seismic hazard model for Beirut. An earthquake catalogue has been compiled covering the time span between 48 and 2010 AD and for the area bounded by 27°N - 37°N and 31.5°E - 39°E. Ground motion prediction equations appropriate for each of the tectonic regimes present in the region have been selected and the uncertainty in each element of the hazard assessment has been included in the assessment using logic tree methodology. Uniform hazard spectra for 475 and 2475 year return periods have been derived. Seismic design spectrum in accordance with the IBC 2009 codes provisions is also presented

*Keywords: Beirut, Dead Sea Transform, Seismic Hazard, code based design*

## 1. INTRODUCTION

This paper presents new probabilistic seismic hazard estimates for Beirut. While a number of PSHA studies for the Lebanon and adjacent countries have been carried out in the past, there is a large variability in the expected ground motion levels reported for Beirut (0.16g to 0.32g for a 475-year return period). Early seismic hazard studies have made crude assumptions regarding the interpretation, location and seismic potential of the different sources affecting the hazard in Lebanon. However, in recent years new geological, geodetic and paleoseismic data along the Lebanese restraining bend as well as bathymetric mapping of the Mount Lebanon Thrust (MLT) offshore Lebanon have provided further insights on the tectonic setting, slip partitioning and seismic potential of the faults crossing Lebanon. Instrumental seismicity is generally sparse within the Lebanese restraining bend, although historical records document the occurrence of large earthquakes (M>7.0) in the region. The large magnitude of these historical events contrasts with the relative lack of large earthquakes during most of the instrumental period. The largest event observed in recent times is the $M_W$=7.3 Gulf of Aqaba earthquake of 1995 which confirmed the long-term potential for large earthquakes along the Dead Sea Transform Fault. The results of this study allow seismic design criteria to be derived, following the definitions in IBC (2009), rather than relying on the now obsolete UBC (1997) criteria that form the background to the Lebanese government issued Decree 11266 (1997). The Lebanese decree indicates a seismic zone parameter of 0.2g (Zone 2B) should be used for the whole of the Lebanon.

## 2. REGIONAL TECTONIC SETTING

The tectonic setting of the Eastern Mediterranean region is the result of the interaction of three major plates: the Arabian, African and Eurasia Plates, and two sub-plates: the Anatolian and Sinai. The Eastern Mediterranean region is tectonically very complex and contains a variety of tectonic regimes.

In the south, the Red Sea represents an environment of continental rift. Transcurrent-type movements occur along the Dead Sea Transform Fault (DSTF) and the East Anatolian Fault (EAF). Oceanic collision occurs along the Hellenic and Cyprian Arcs (See Figure 1a).

The DSTF is a ~1000 km long strike-slip fault system and constitutes the continental plate boundary between the Arabian and African plates. It extends from the Gulf of Aqaba, at the northern end of the Red Sea spreading centre, to the Arabia-Eurasia collision, southeast of Turkey (See Figure 1a). It transfers part of the Arabia-Africa divergent motion in the Red Sea into the convergence motion between Eurasia and Arabia (Wdowinski et al., 2004). Some of the Arabia-Africa divergent motion in the Red Sea is also transferred to the Gulf of Suez, which forms the boundary between Africa and Sinai. Previous studies have estimated the plate motion along the DSTF to be within a range of 4-10 mm/yr (e.g., Meghraoui et al., 2003; Gomez et al., 2003; Daeron et al. 2005).

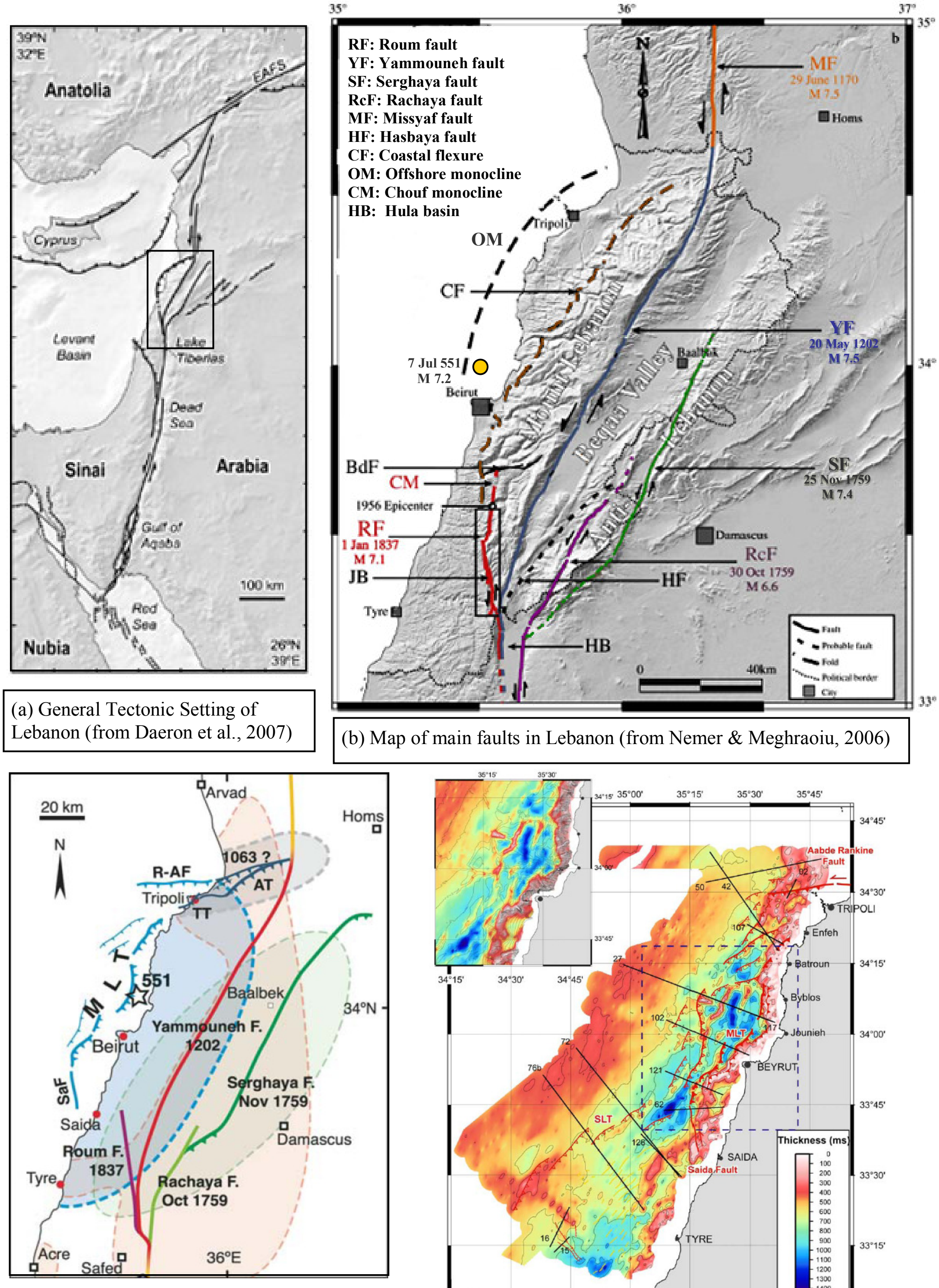
## 2.1. Local Faulting in Lebanon

The DSTF can be divided into two main sections joined by a ~200 km long restraining bend along Lebanon. Within the Lebanese restraining bend, the DSTF splits into five main fault branches: the Roum, Yammouneh, Seghaya, Rachaiya and Hasbaya faults (Figure 1a and 1b). Of these only the Yammouneh Fault crosses the whole country and is considered to be the main fault branch of the DSTF within Lebanon, transferring most of the slip of the DSTF (e.g., Daeron et al., 2004). Recent studies including paleoseismic (Gomez et al., 2003; Daeron et al. 2004, 2005; Nemer & Meghraoui 2006) and geodetic (e.g. Wdowinski et al. 2004) investigations along the different fault strands within the bend have indicated that these faults are active and therefore they are likely to affect the hazard in Lebanon.

Despite the lack of large earthquakes during the instrumental period, historical records suggest the seismic potential of the various faults (e.g., Ambraseys et al., 1994; Ambraseys & Jackson, 1998). It has been suggested that Roum fault is the most active strand of the DSTF in Lebanon (e.g., Girdler, 1990; Butler, 1997; Darawcheh et al., 2000; Khair, 2001) and the source of a large ($M_S$ 7.2) event in 551 AD, which destroyed most of the coastal cities of present day Lebanon (See Figure 1c). Ambraseys et al. (1994) located the earthquake inland and to the east of Beirut and attributed this event to the Roum Fault, but Darawcheh et al. (2000) subsequently proposed that this event was located offshore Beirut and the result of slip along a possible extension of the Roum Fault into the Mediterranean Coast. More recently, a study by Nemer & Meghraoui (2006) indicated the lineament of the Roum Fault does not extend offshore and instead it disappears at ~ 33.67°N, where the fault bends northward and merges with the Chouf monocline (CM in Figure 1b).

Activity along the Yammouneh Fault has also been a topic of debate. Butler et al. (1997) suggested that the northern part of Yammouneh Fault has been inactive over the last 5-6 million years and that the Roum Fault was probably the principal active structure of the DSTF. Recent paleoseismic investigations have however indicated that the Yammouneh Fault is tectonically active and had ruptured in infrequent but large earthquakes (M>7.0) (e.g., Daeron et al., 2005, 2007; Nemer et al. 2008), including a M7.5 event in 1202 (Figure 1b and 1c). Despite the apparent lack of present day seismicity, all recent studies reviewed suggested that the Yammouneh Fault is more likely to accommodate most of the plate motion within the Lebanese restraining bend (e.g., Gomez et al., 2003; Daeron et al., 2004; Gomez et al., 2007). Based on paleoseismic data, the slip rate on this fault was constrained to be 3.8-6.4 mm/yr (Daeron et al. 2004; Gomez et al., 2007), taking up most of the overall slip of the DSTF within the Lebanese restraining bend.

Similarly, the Serghaya Fault had been regarded as inactive (e.g. Butler et al. 1997), but recent studies (e.g., Gomez et al., 2001; 2003; Daeron et al. 2005) have presented palaeoseismic evidence of active strike-slip movement along this fault and have postulated it as the source of one event in November 1759 (Figure 1b and 1c). On the basis of the identification of active thrust faults in the Tripoli region, Tapponnier et al. (2001) proposed the existence of a large thrust fault system, the Mount Lebanon thrust (MLT) in the offshore area between the cities of Saida and Tripoli (Figure 1d). The existence of this offshore thrust system has also been confirmed by geophysical data (Elias, 2007; Carton et al., 2009). The MLT has recently been proposed as the source of the 551 earthquake (M7.2) offshore of Lebanon (Elias et al., 2007) (Figure 1d).




(a) General Tectonic Setting of Lebanon (from Daeron et al., 2007)

(b) Map of main faults in Lebanon (from Nemer & Meghraoiu, 2006)

(c) Possible sources of large historical earthquakes in Lebanon. Coloured areas indicate the regions where intensities >VIII were reported (From Elias et al., 2007)

(d) Location of Mount Lebanon Thrust (MLT) System (From Carton et al. 2009)

**Figure 1.** Tectonic Setting and location of main faults in Lebanon. The inset in (a) shows the location of the Lebanese Restraining Bend

## 3. SEISMIC HAZARD ASSESSEMENT

New probabilistic seismic hazard estimates for Beirut are produced in this study. A seismic source model has been developed based on recently published geologic/tectonic interpretations and a compiled earthquake catalogue. Earthquake recurrence parameters for areal sources have been determined by fitting a Gutenberg–Richter truncated exponential model to the annual earthquake data. For planar sources within Lebanon, earthquake recurrence based on slip rates has also been used. The methodology adopted is based on that originally proposed by Cornell (1968), modified to include integration over the aleatory variability of the ground- motion prediction equations. The uncertainty the various elements (seismic source models, ground-motion prediction equations) have been included in the assessment using logic tree approach.

### 3.1. Earthquake Catalogue

An earthquake catalogue has been compiled for the period from 48AD to 2010 and for the area bounded by 27°N–37°N and 31.5°E–39°E. Earthquake data have been collected from various sources including compilations by Degg (1990), Ambraseys et al. (1994), Ambraseys & Jackson (1998), Elnashi & El-Khoury (2004), amongst others. Instrumental data were compiled from the Engdahl-Hilst-Buland (EHB) Bulletin as well as the on-line catalogues of International Seismological Centre (ISC), National Earthquake Information Centre (NEIC) and Global Centroid Moment Tensor (GCMT) database. As a result of the variety of sources used in the catalogue conversions to a uniform magnitude scale were carried out. This was also required to ensure compatibility with the magnitude definition used in the ground-motion models. The moment magnitude scale ($M_W$) was adopted and other magnitude estimates were converted to $M_W$ using the Akkar et al. (2010) magnitude conversions.

Since it is a requirement in normal probabilistic seismic hazard studies that seismicity be treated as Poissonian (e.g., Reiter, 1990), subsidiary events (i.e. aftershocks and foreshocks) have been removed from the composite catalogue using the windowing procedure proposed by Gardner and Knopoff (1974). The final filtered catalogue used for the seismic hazard calculations is shown in Figure 2. Finally, the statistical completeness of the earthquake catalogue was assessed using the method proposed by Stepp (1972). The following magnitude and time ranges are considered to be complete in the compiled earthquake catalogue:

1750 to 2010 for $M_W \geq 6.0$
1920 to 2010 for $M_W \geq 5.0$
1964 to 2010 for $M_W \geq 4.5$
1984 to 2010 for $M_W \geq 4.0$

### 3.2. Seismic source zone characterisation

This study's seismic source delineations are shown in Figure 2. They have been defined based on a combination of earthquake locations and current understanding of the regional geology and tectonics as well as existing source zonings for the region. It includes 11 areal sources and 3 planar sources that represent specific faults identified in the Lebanon. It can be seen that spatial pattern of seismicity of the region strongly reflects the location of the major tectonic features and the source zones developed attempt to represent this distribution. Areal Zone 1, 2, 4 and 9 follow different fault zones along the DSTF. In particular, Zone 1 and 9 represent the south and north sections of the DSTF, which are joined by Zone 4 that corresponds to the Lebanese restraining bend. Zone 4 thus contains the seismicity that can be potentially ascribed to the main faults within Lebanon. Because of the uncertainty in the seismicity model for the Lebanese restraining bend, the main fault strands within the bend (Roum, Yammouneh and Serghaya-Rachaya Faults) are alternatively modelled as individual planar sources with earthquake recurrence described by slip rates. These two variations are incorporated in a logic tree and assigned equal weights.

Zone 2 represents the southernmost part of the DSTF, which runs along the Gulf of Aqaba and where a $M_W$=7.3 earthquake occurred in 1995. Zones 6 and 8 represent the Gulf of Suez, the Red Sea and the Sinai Peninsula respectively. Zone 5 corresponds to the zone of faulting that is shown moving northeast from the Jordan Valley into Syria. Zone 3 represents the area offshore of Israel and southern Lebanon that appears to have increased seismicity compared to the background. Zone 7 represents the Mount Lebanon Thrust (MLT) system mapped offshore Lebanon and includes the estimated epicentre for the 551 earthquake (M 7.2). This zone's boundaries are based on the MLT location reported by Carton et al. (2009). Finally, Zone 10 represents the oceanic convergence between the Nubian and Anatolian plates, along the Cyprian Arc and Zone 11 represents the area southeast of Turkey, adjacent to the intersection between the Cyprian Arc, the Dead Sea Fault (DSTF) and the East Anatolian Fault (EAF).

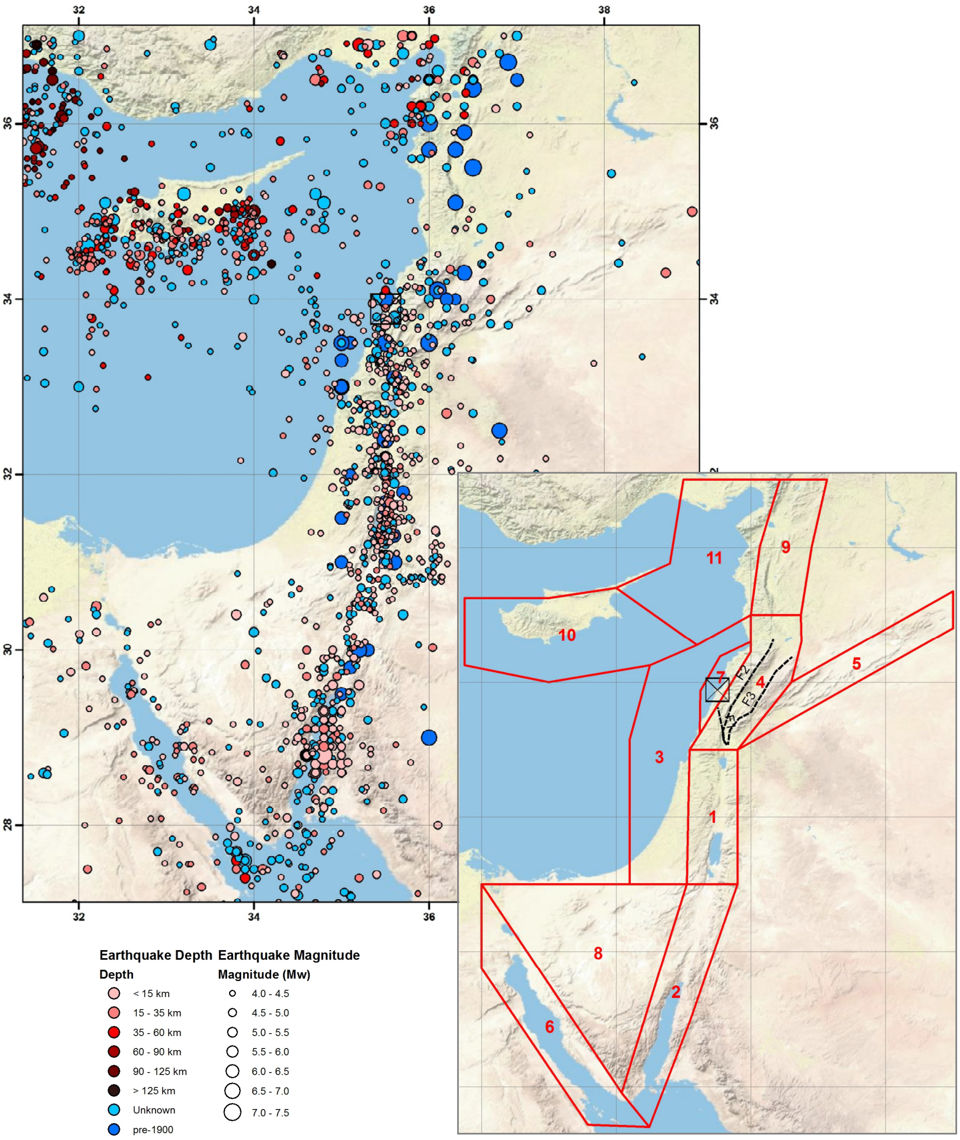



**Figure 2.** Earthquake catalogue (not including subsidiary events) and seismic source delineations

The truncated exponential model has been adopted to represent the distribution of earthquake magnitudes on each areal source. The truncated exponential model is based on the Guttenberg-Richter relation:

$$Log\ N(m) = a - bm \quad (1)$$

Where $N(m)$ is the cumulative number of earthquakes with magnitude greater than $m$ occurring per unit of time, $a$ is the activity rate, generally defined as the number of earthquakes with magnitude greater than 4 and $b$ is the slope of the magnitude-recurrence relationship. The complete part of the catalogue together with Eq. 1 (truncated at a minimum and maximum magnitude bounds), are used to compute the values of $a$ and $b$ (along with their associated variability) for each areal zone through application of Weichert's approach (Weichert 1980). Table 1 lists these values and the range of maximum magnitudes assigned for each zone.

**Table 1.** Magnitude recurrence parameters for areal sources

| Zone No. | Zone name | b-value | | Activity rate [N>4/yr] | | Maximum magnitude | |
|---|---|---|---|---|---|---|---|
| | | mean | sigma | mean | sigma | observed | assigned |
| 1 | Southern Dead Sea Transform Fault | 0.99 | 0.05 | 2.00 | 0.09 | 7.1 | 7.4±0.2 |
| 2 | Arava & Aqaba Faults | 0.78 | 0.04 | 3.20 | 0.21 | 7.2 | 7.4±0.2 |
| 3 | Mediterranean Coast | 0.95 | 0.10 | 0.70 | 0.05 | 7.0 | 7.4±0.2 |
| 4 | Lebanese restraining bend | 0.87 | 0.07 | 0.90 | 0.07 | 7.4 | 7.6±0.2 |
| 5 | Syrian Fault Zone | 0.89 | 0.20 | 0.18 | 0.05 | 5.0 | 6.5±0.2 |
| 6 | Gulf of Suez | 1.01 | 0.10 | 1.30 | 0.14 | 6.4 | 7.0±0.2 |
| 7 | Mount Lebanon Thrust | 1.02 | 0.12 | 0.40 | 0.04 | 7.2 | 7.4±0.2 |
| 8 | Sinai Desert | 0.92 | 0.23 | 0.50 | 0.09 | 5.2 | 6.5±0.2 |
| 9 | Northern Dead Sea Transform Fault | 0.80 | 0.13 | 0.18 | 0.05 | 7.4 | 7.6±0.2 |
| 10 | Cyprus Convergence | 0.83 | 0.04 | 3.25 | 0.13 | 6.8 | 7.0±0.2 |
| 11 | Cyprian Arc-Dead Sea Transform - East Anatolian Fault junction | 0.89 | 0.08 | 1.35 | 0.15 | 7.2 | 7.4±0.2 |

The Roum, Yammouneh and Serghaya-Rachaya Faults were alternatively modeled as individual planar sources with earthquake recurrence described by the characteristic earthquake model (Youngs & Coppersmith, 1985). Table 2 lists the parameters adopted for the planar. The maximum magnitudes were chosen based on the displacements reported by different geologic and paleoseismic studies as well as their association with large historical events (Figure c). The proposed maximum magnitudes for the different fault strands within the Lebanese restraining bend are consistent with those used by the recent seismic hazard study of Al-Tarazi and Sandovol (2007).

**Table 2.** Parameters assumed for the fault sources within the Lebanese restraining bend

| Fault No. | Fault Name | Approx. Length [km] | Approx. Dip [°] | $M_{max}$ | Slip rate [mm/yr] | Slip rate Reference |
|---|---|---|---|---|---|---|
| 1 | Roum Fault | 65 | 90 | 7.2±0.2 | 0.95±0.1 | Nemar & Megharoui (2006) |
| 2 | Yammouneh Fault | 142 | 90 | 7.5±0.2 | 5.10±1.3 | Daeron et al. (2004), Gomez et al. (2007) |
| 3 | Serghaya-Rachaya Faults | 105 | 90 | 7.2±0.2 | 1.40±0.2 | Gomez et al. (2003) |

### 3.3. Ground-motion prediction equations (GMPEs)

GMPEs appropriate for each of the tectonic regimes present in the region have been selected. Focal mechanisms of earthquakes along the DSTF are consistent with strike-slip faulting. Ground motions in these zones have modelled by the shallow-crustal equations of Boore & Atkinson (2007), Campbell & Bozorgnia (2007) and Akkar and Bommer (2010) using strike-slip settings. The same models where used for the MLT with reverse mechanisms settings. Events along the Cyprus convergence are consistent with reverse faulting, although there are also some strike-slip events (Wdowinski et al., 2006). Reverse events occur at depths less than 60 km and are therefore expected to be associated to faulting at the interface between the Nubian and Anatolian plates and are modelled by the interface equations of Atkinson and Boore (2003, 2008) and Youngs et al. (1997). Earthquakes along the junction between the Cyprian Arc, DSTF and the EAF (Source Area 11) display a variety of focal mechanisms, including strike-slip and normal mechanism events, and are the result of transcurrent motion (Wdowinski et al., 2006), although there may well be some events related to subduction processes. This region is considered a mixed region and hence GMPEs for subduction and shallow crustal events are used. In all cases the geometric mean values were used.

### 3.4. Logic tree

The uncertainty in the b-value of each areal source zone has been taken into account by assigning different weights to the mean estimate (0.60 weight) and mean ± 1 sigma values (0.20 weight each). The same approach was followed to account for uncertainty in the slip rate of the planar sources. A range of maximum magnitude values were considered for each zone weighted 0.20, 0.60 and 0.20, respectively. The Akkar & Bommer (2010), which includes dada from the Euro-Mediterranean region, has been assigned a weight of 40%. Equal weights (30%) have been assigned to Boore & Atkinson (2007) and Campbell & Bozorgnia (2007) models. For the Cyprus convergence, equal weights of 0.5 have been assigned to the Atkinson & Boore (2003, 2008) and Youngs et al. (1997) subduction equations. To model the uncertainty in the seismicity model for the Lebanese restraining bend, an areal source (Zone 4) and planar sources (F1, F2 and F3) are considered with equal weights.

## 4. HAZARD RESULTS

The probabilistic seismic hazard calculations were carried out using Arup's in-house program Oasys SISMIC, which has recently been validated using the Pacific Earthquake Engineering Research Center (PEER) tests. This study's bedrock (NEHRP site class B) PGA values and spectral accelerations at 0.2 and 1.0 sec at city of Beirut having 10% and 2% probability of exceedance in 50 years (475 and 2475 years return periods) are compared with those from existing seismic hazard studies in Table 3.

**Table 3.** Comparison of this study with mean hazard values from existing seismic hazard studies

| Return period (years) | Reference | PGA (g) | Sa (0.2s) (g) | Sa (1s) (g) |
|---|---|---|---|---|
| 475 | GSHAP | 0.25 - 0.30 | - | - |
| | European Seismological Commission (2003) | 0.24 - 0.32 | - | - |
| | Elnashai and El-Khoury (2004) | 0.16 | - | - |
| | Al-Tarazi and Sandovol (2007) | 0.25 | - | - |
| | **This Study** | **0.34** | **0.80** | **0.16** |
| 2475 | USGS design maps (approx. based on GSHAP values) | *0.60* | *1.49* | *0.60* |
| | Elnashai and El-Khoury (2004) | 0.28 | - | - |
| | **This Study** | **0.61** | **1.45** | **0.34** |

It can be seen that this study's PGA values are generally larger than previous estimates. By contrast the PGA estimates reported by Elnashai and El-Khoury (2004) are significantly lower than other studies for the region. Spectral accelerations for the 2475 year return period at 0.2 sec and 1.0 ($S_S$ and $S_1$ parameters in IBC 2009) are also reported in this table. This study's values may be compared to those reported in the USGS worldwide seismic design maps (https://geohazards.usgs.gov/secure/designmaps/ww/) application, which are based on rough approximations based on the PGA for 475 year return period from GSHAP. Table 3 shows that the PGA and 0.2 sec values compare well to this study.

## 5. SEISMIC DESIGN REQUIREMENTS

The Lebanese Decree 11266 provides guidance on the seismic design for the Lebanon. This code provides general guidelines and appears to follow the same principals of the 1994 version of the Uniform Building Code (UBC). Though not explicitly stated in the decree, it is assumed that the zone parameter relates to a 10% chance of exceedance in 50 years (475-year return period), as stated in UBC. It is also noted that a seismic zone parameter of 0.2 for the whole Lebanon equates to Zone 2B in UBC (1997). A comparison the computed uniform hazard spectra for 475 and 2475 year return period and the Lebanese 11266 and internationally used seismic design codes is presented in Figure 3. This shows the 475-year spectrum is more conservative than the UBC 1997 spectrum for zone 2B at periods less than ~0.75 sec, but less conservative at longer spectral periods. It is also observed that the Lebanese decree 11266 constitutes a lower bound to the spectra. For contrast, the UBC 1997 zone 3 spectrum is also provided, which shows the over conservatism of the zone 3 spectrum at periods beyond 0.25 sec.

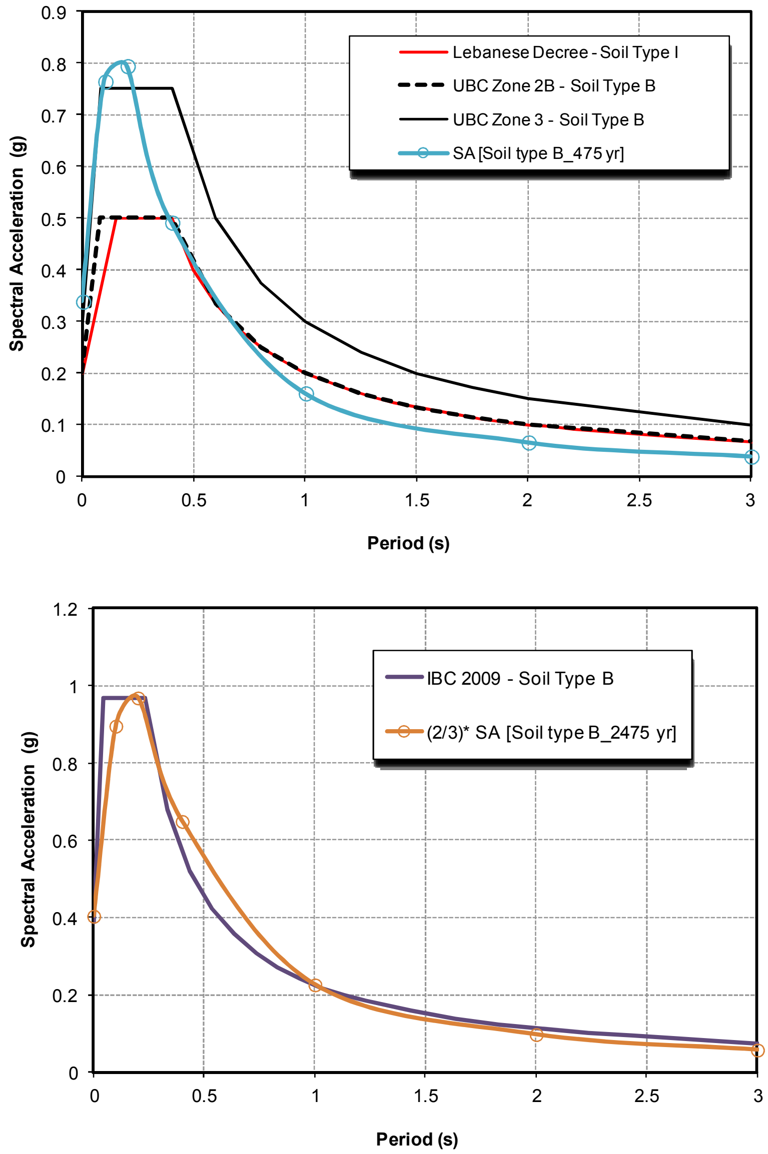



**Figure 3**. Comparison of code spectra with bedrock (Site class B) uniform hazard spectra calculated for the city of Beirut at 10% and 2% probability of exceedance in 50 years (475 and 2475-yr return period).

## 6. CONCLUSION

New probabilistic seismic hazard estimates for Beirut are produced in this study. A seismic source model has been developed based on recently published geologic/tectonic interpretations and an earthquake catalogue compiled for this study. A standard probabilistic seismic hazard methodology has been adopted and the uncertainty the various elements (seismic source models, ground-motion prediction equations) have been included in the assessment using logic tree approach. This analysis has considered the potential for earthquake activity associated with the recently mapped Mount Lebanon Thrust as well as the main faults within the Lebanese retraining bend.

The study has also shown that the existing Lebanese decree potentially underestimate the seismic criteria for structures with a natural period of less than 0.75s, which is equivalent to structures less than about 20m high. Furthermore, there is a potential load reduction for taller structures.

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