

UPDATED SEISMIC HAZARD FOR LEBANON AND IMPLICATIONS ON MICRO-ZONATION OF THE GREATER BEIRUT AREA

Salah SADEK¹ and Mohamad HARAJLI²

ABSTRACT

Lebanon straddles an important and clearly defined fault system in the eastern Mediterranean. The country lies across the northern segment of the Dead Sea fault and has suffered many devastating earthquakes which are part of the historical record.

The seismic hazard evaluation for Lebanon was revised in light of recent data obtained through off-shore geophysical mapping along the Lebanese coast, which revealed extensions of the “Roum Fault” forming an “arc” which appears to bypass the main south-north projection of the “Yammounéh Fault”. The seismic hazard evaluation was conducted using probabilistic methods, with potential sources of seismic activity identified along with their pertinent recurrence relationships. The sensitivity of the results to various assumptions regarding the seismic sources in the Lebanese segment and choice of attenuation relationship was evaluated. Updated maps of peak ground acceleration contours based on 10% probability of exceedance in 50 years were produced.

A Geographic Information System (GIS) platform and framework were developed and adapted to incorporate the results of the updated seismic hazard analysis in order to produce maps of earthquake geo-hazards for the Greater Beirut Area. The geo-hazards that were assessed in this study were limited to site specific ground amplification. The process of creating the base GIS framework and the collection and generation of pertinent data is described in the paper along with the methodology developed for the generation of the hazard maps. Finally, the results of the study are discussed and evaluated.

Keywords: Seismic hazard, ground amplification, GIS, seismic zoning.

INTRODUCTION

Lebanon occupies 225 km of the 600 km long Eastern Mediterranean coastal region and straddles the ~1000 km long fault which extends from the seafloor spreading in the Red Sea to the Taurus mountains in southern Turkey. This fracture system, known as the Levantine or Dead Sea system is an important tectonic feature, which accounts for the bulk of seismic activity in the Eastern Mediterranean.

In its southern segment, which extends from the Gulf of Aqaba to the Sea of Galilee and the Hula depression in south Lebanon, the Dead Sea fault system strikes in a more or less N-S direction. However, when entering Lebanon through the Galilee heights, it changes into a more complex system of braided strike-slip faults (Wally 1988), known as Roum, Yammounéh, Hasbaya, Rachaya, and Serghaya (Figure 1). The most significant among these faults is the Yammounéh which forms the

¹ Professor, Department of Civil and Environmental Engineering, American University of Beirut, Lebanon, Email: salah@aub.edu.lb

² Professor, Department of Civil and Environmental Engineering, American University of Beirut, Lebanon.

western boundary of the Bekaa valley, and which represents the main northward continuation of the Dead Sea fault system to the Ghab fault in Syria, and then on to the Taurus-Zagros thrust in southern Turkey.

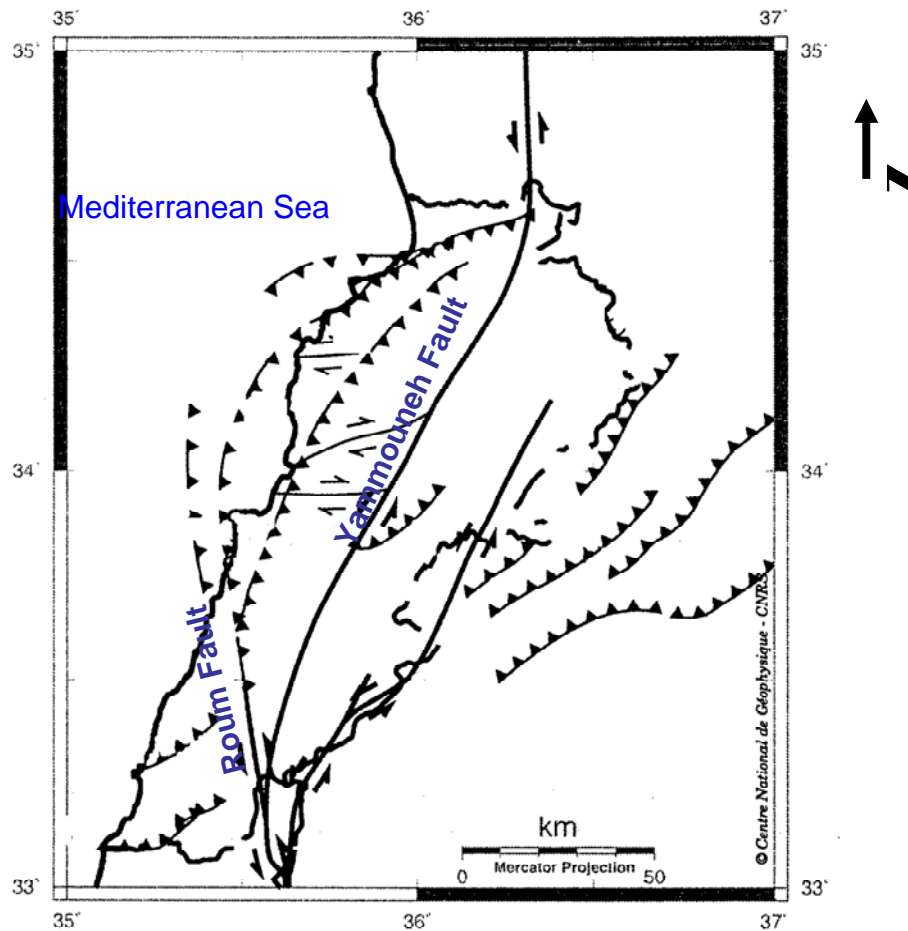


Figure 1. Major faults identified across Lebanon

A review of the seismic activity in Lebanon and the Eastern Mediterranean demonstrates that this part of the world has been shaken since 2000 B.C. by strong earthquakes affecting present day Lebanon, Syria, Jordan, Israel and Palestine. Three earthquakes stand out in the history of seismic activities in Lebanon: the earthquakes of 551 A.D., 1202 A.D and 1759 A.D (two events). The magnitudes of these earthquakes were estimated based on historical accounts, to be in excess of 7.0, and caused devastating destruction in most coastal cities including Beirut, as well as the ancient city of Baalbeck inland. Other major earthquakes of varying magnitudes were established through the historical record and reported by a number of researchers (Plassard and Kogoj, 1981; Ambraseys and Melville, 1988; Ambraseys and Barazangi, 1989). According to Ambraseys and Barazangi (1989), during the last millennium alone, more than 8 strong earthquakes with magnitude greater than 6.5 have struck along the northern continuation of the Dead Sea fault in Lebanon and Syria. Furthermore, earthquakes on the seabed between Cyprus and Lebanon, some of which are close to the coastal line, are very frequent. These earthquakes may affect a large number of heavily populated and developed cities and towns along the coastal belt of Lebanon. Recent studies have allowed for a more reliable mapping of the offshore extension of the Roum Fault segment and indicate the presence of arc normal fault possibly running parallel to the Yammouneh as shown in Fig. 1 (NCGR-Bhannes Lebanon, 2006).

The last sizable inland earthquake that struck Lebanon in the past century is the double shock of March 16, 1956. The epicenter was estimated close to the northern inland segment of the Roum fault and the magnitude was measured at 5.8 by the Bhannes Seismological Observatory in Lebanon. This earthquake left 136 dead, 6000 homes destroyed and about 17000 heavily damaged. More recently, an

earthquake of magnitude 5.3 struck Lebanon on March 21, 1997. The epicenter was estimated by the same observatory to be almost at the same location (Roum fault) as the double shock of March 16, 1956. The earthquake reached Beirut with an intensity of about VI on the Modified Mercalli (MM) intensity scale and resulted in high levels of shaking for a short duration of about 6 seconds.

In the past several years, a number of studies and research efforts have attempted to evaluate the seismic hazard of neighboring countries (Yucemen, 1992; Malkawi et al., 1995). This paper presents the results of a study that was undertaken to evaluate the seismic hazard of Lebanon. A catalogue of seismic events including instrumental and historical data was developed, the seismic sources that affect the hazard in Lebanon were identified, and the recurrence relationships of these sources were generated. The hazard results are presented in a map of peak ground acceleration contours based on 10 percent probability of exceedance in 50 years. The results for the city of Beirut are reported.

The Greater Beirut Area (GBA) is the largest metropolitan center in Lebanon harboring more than half of the country's population. It is also an area that exhibits a high variety of soil types and geologic and geomorphologic conditions. The seismic geo-hazards evaluations for the GBA built on the seismic hazard analysis and were restricted to ground amplification. In order to produce geo-hazard maps for the GBA, the effect of soil strata underlying the area, local topography, was incorporated in the analyses. The evaluation of the local soil conditions and the estimation of their influence on the total seismic hazard from ground shaking involved the collection, interpretation and mapping of all available geological and geotechnical data for the GBA.

SEISMIC HAZARD ANALYSIS

A detailed description of the hazard analysis method adopted in this study was presented in an earlier paper (Harajli et al., 2002). In what follows some of relevant aspects of the analysis are presented with particular focus on seismic sources and recurrence relationships and fault system model used.

Seismic Sources and Earthquake Recurrence Relationships

The seismic sources and their earthquake recurrence relationships were determined by compiling instrumental as well as historical earthquake data pertaining to the seismic activity inside Lebanon and vicinity (Plassard and Kogoj, 1981; Ambraseys and Melville, 1988; Ambraseys and Barazangi, 1989), and by relying in part on earlier studies undertaken to evaluate the seismic hazard of neighboring countries. A catalogue of historical and instrumental seismic records in this part of the world, going back to 1365 B.C., is presented by Harajli et al. (1994).

Since the seismic hazard evaluation of Lebanon is mainly influenced by the seismic activity within the country or at a close proximity to it, efforts were made to define the seismic sources and establish the earthquake recurrence relationship in the Lebanese segment. In addition to a region defined as the Lebanon region, two neighboring and potentially contributing areas were identified. They are noted as the Mediterranean region, and the Southern segment of the Dead Sea fault, respectively. In what follows the sources are further described and their seismic characteristics presented.

Neighbouring regions

Two additional seismic sources were considered as they may influence the seismic hazard analysis of Lebanon, in addition to the northern extension of the Lebanese system inside Syria for which the earthquake recurrence relationships developed for the Lebanon segment are assumed to apply:

(a) *Southern segment of the Dead Sea fault*: Modeled as a line source, it extends in a S-N direction from the southern part of the Dead Sea (Latitude 31.0°N, Longitude 35.4°E) to the Galilee heights in south Lebanon (Latitude 33.3°N, Longitude 35.6°E), with a total length of about 256 km. This segment is represented in Figure 2.

(b) *Mediterranean region*: Modeled as an area source, it includes earthquake activity south of Cyprus. This area source is bounded approximately between Longitudes 32°E and 34.9°E, and Latitudes 33.5°N and 35.3°N, with an approximate area of 50,000 sq.km. This area is also represented in Figure 2.

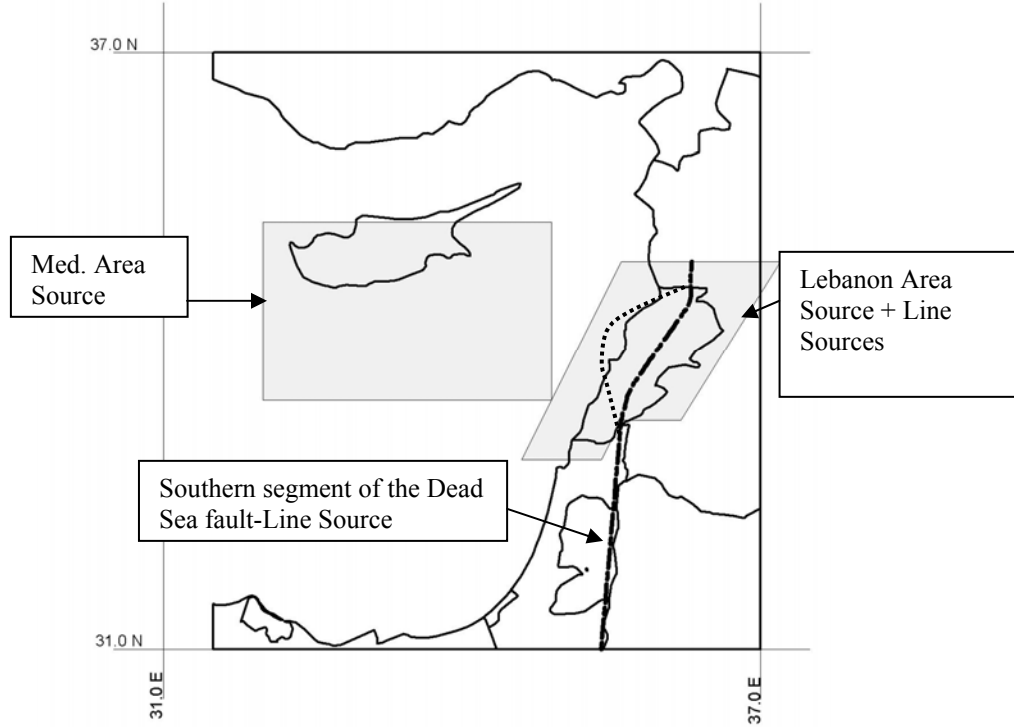


Figure 2. Schematic of region and model

Several studies have concentrated on evaluating the seismic activity of these sources and many equations were proposed to describe their earthquake recurrence relationships (Ben-Menahem, 1981 and Yucemen, 1992). In this study, the annual earthquake recurrence relationships proposed by Yucemen (1992) were adopted:

Southern segment of the Dead Sea fault:

$$\text{Log}(N \geq M) = 2.64 - 0.75M \quad (1)$$

Mediterranean region:

$$\text{Log}(N \geq M) = 1.40 - 0.45M \quad (2)$$

Based on historical records and rupture length-magnitude relationships, the maximum earthquake magnitude for the Dead Sea fault and the Mediterranean Region were estimated (Yucemen 1992) to be 7.5 and 7.0, respectively.

The Lebanon region

Instrumental data comprising about 100 events in the period between 1903 to 1999 with surface magnitudes ranging from $M_s \sim 3.0$ to 6.0, in addition to historic data were used in producing the recurrence relationship for the Lebanon segment. A complete breakdown and representation of the instrumental data by magnitude and time span is included in Figure 3.

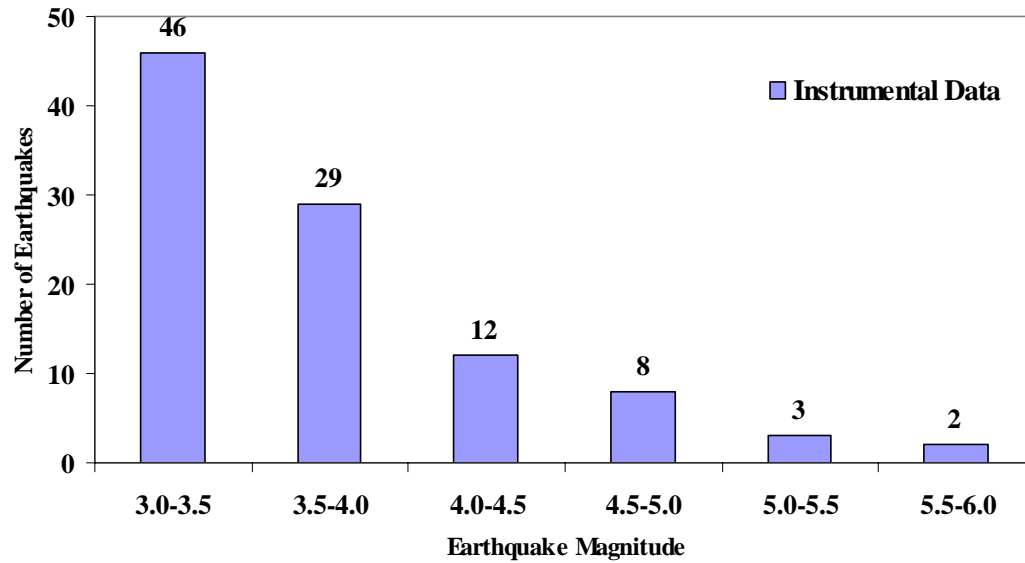


Figure 3. Breakdown of instrumental earthquake records (1903-1999) by magnitude, Ms

The following relevant observations and assumptions were considered for modeling the seismic sources and deriving their earthquake recurrence relationships:

- (i) The seismic events triggered by the fault system in the Lebanese segment under evaluation are enclosed within the area zone defined in Figure 2 (area = 25,000 sq.km). The earthquakes bordering the prescribed zone to the south are assumed to belong to another seismic source, namely, the southern segment of the Dead Sea fault system discussed earlier.
- (ii) Since geological studies to predict the maximum earthquake magnitude are not available for the fault system in Lebanon, it is necessary to rely on historical records and to assume, with reasonable accuracy, that the maximum earthquake magnitude in the Lebanese segment is equal to 7.5. This magnitude is also consistent with the one proposed by Yucemen (1992) for the Dead Sea fault system used in studying the seismic hazard of Jordan and vicinity.
- (iii) According to Ambraseys and Barazangi (1989), the major established historical earthquakes had struck along a 350 km long stretch of the northern continuation of the Dead Sea fault system in three short periods of paroxysmal activity in 1157-1202, 1404-1407, 1759-1796, about 200 to 350 years apart. Assuming equal probability of earthquake occurrence anywhere along this stretch, the conservative return period of 200 years, taken to correspond to the maximum earthquake of magnitude 7.5, is equivalent to a return period of about 450 (say 500) years along the approximately 150 km long northerly stretch inside Lebanon.

Based on the observations and assumptions presented above, the following seismic source model for the Lebanese segment as shown in Figure 2 was studied: Large earthquakes (with magnitudes greater than 6) for the last 900 years or so had their epicenters along the Yammouneh fault and its northern continuation to the Ghab fault in Syria. As such, it is reasonable to assume that while earthquakes of magnitude $M \leq 6.0$ have equal probability of striking anywhere within the area source defined in Fig. 3, major inland earthquakes ($M > 6.0$), including the maximum earthquake of magnitude 7.5, strike predominantly, and with equal probability, along the 150 km long Yammouneh fault line. This restriction imposed on the location of large magnitude earthquakes is compatible with the concept of seismic locking of the Yammouneh fault (Walley, 1988). In mathematical terms, when used in conjunction with seismic hazard analysis, it is similar, in some respect, to the use of distance probability distribution functions (Der-Kiureghian and Ang, 1977), which are employed when earthquakes are more likely to occur along some parts of the seismic source than along others. As

such, the seismic source for the Lebanon segment becomes equivalent to an area source with maximum magnitude equal to 6.0 plus a line source along the Yammouneh fault line (length = 150 km) with earthquake magnitudes between 6.0 and 7.5, both of which have a rate of recurrence of earthquake events as described in Eq. (3) and Figure 4.

$$\text{Log}(N \geq M) = 1.89 - 0.62M \quad (3)$$

The analyses based on the model presented, involve the contributions of the Lebanon region as described above (area plus line source), in addition to the contribution from the Southern section of the Dead Sea fault system and the Mediterranean region both defined earlier.

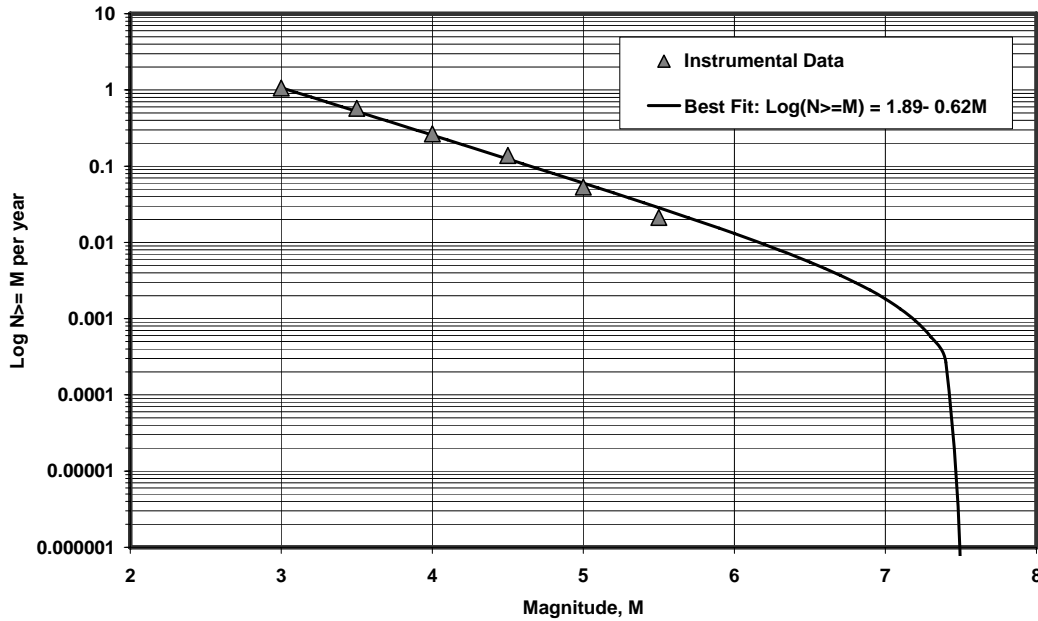


Figure 4. Predicted magnitude-frequency relationship with $M_{\max} = 7.5$

Attenuation Relationships

Due to the fact that data for moderate and strong earthquake records are unavailable, no instrumental data-based relationship has yet been developed to describe the attenuation of ground motion in this part of the world. Therefore, it was necessary to adopt an attenuation relationship from a spectrum of such relations developed worldwide. In this study, the relationship proposed by Ambraseys (Ambraseys 1995) for Europe relating the peak ground acceleration to the distance from the source of energy release, focal depth, and earthquake magnitude is used (Figure 5).

Computation and Results of the Hazard Analyses

In this study, the lower bound earthquake magnitude is taken equal to 5.0 for all seismic sources. Also, it is assumed that the attenuation characteristics of the ground motion are isotropic, i.e independent of the location of the site relative to the source of energy release. The analysis was conducted using the software program, EZ-FRISK (1998, Risk Engineering Inc.– Boulder, Colorado). The program has the capability of handling combinations of seismic sources and multiple attenuation equations and has the advantage of calculating the hazard accurately and efficiently for a wide range of assumptions that are now common in seismic hazard analysis. For the purpose of this study, the region under investigation was divided using approximately a 10 by 10 km mesh, with a total of about 270 different locations of mesh nodal points. The output of the analysis includes the average return periods for 10 different peak ground accelerations varying between 0.05g and 0.5g, the probability that these ground accelerations are exceeded in 50, 100, and 500 years exposure time, and the ground accelerations corresponding to 0.1 probability of exceedance in 50, 100, and 500 years.

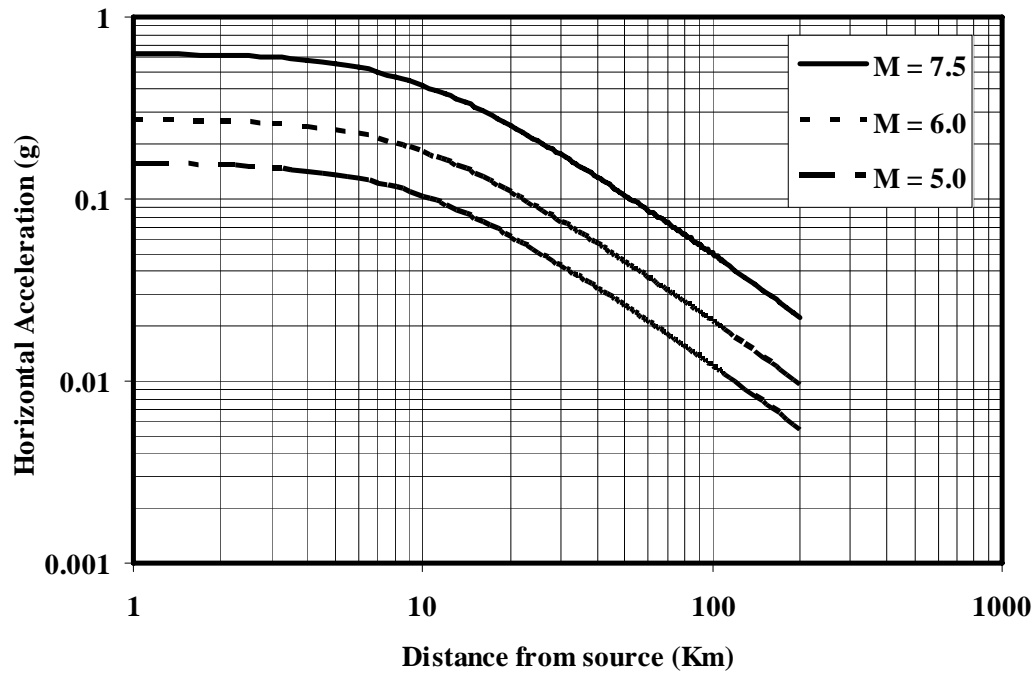


Figure 5. Attenuation relationships used in the analyses (After Ambraseyes, 1995)

Ground acceleration maps

Results of the seismic hazard evaluation showing contour lines of peak ground acceleration (PGA) corresponding to 0.1 probability of exceedance in 50 years for the Greater Beirut Area are shown in Figure 6. The variation of the PGA with the probability of exceedance 50, 100 and 500 years exposure time is shown in Figure 7.

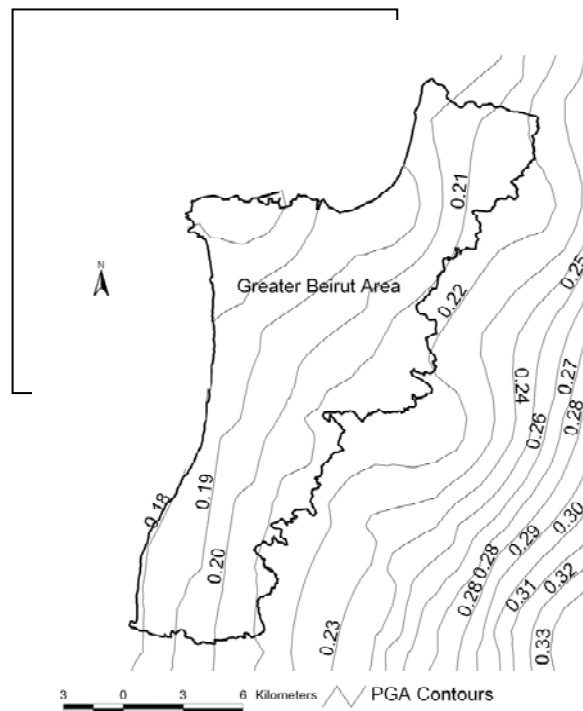


Figure 6. Peak ground acceleration contour lines in the Greater Beirut Area

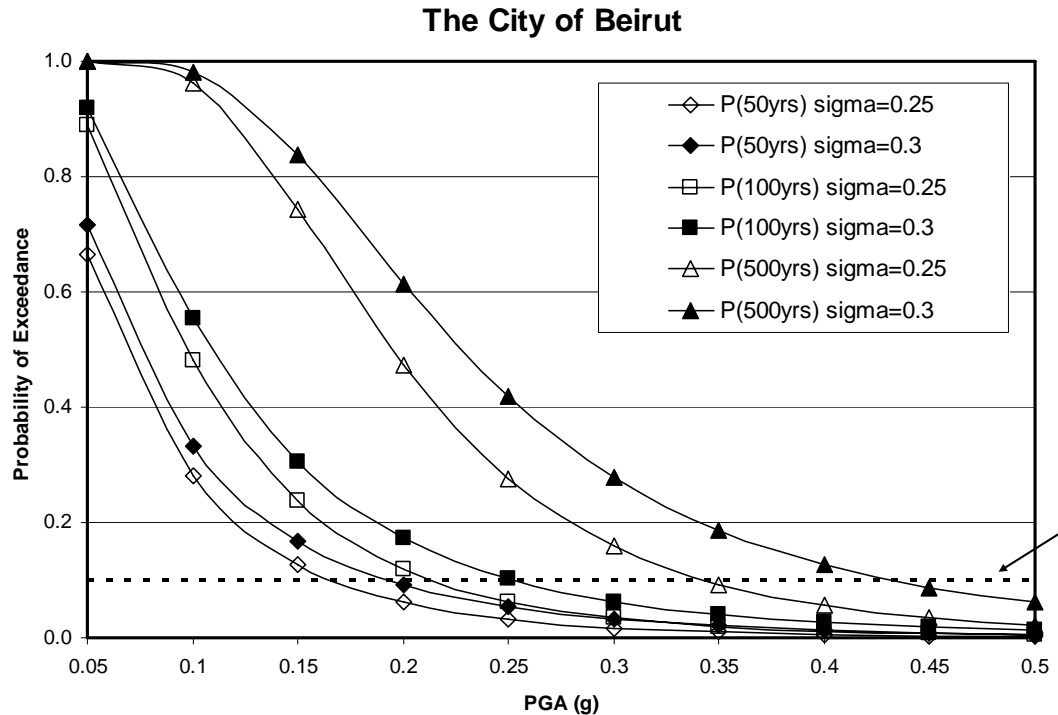


Figure 7. Probability of exceedance vs. peak ground acceleration for Beirut

MICROZONATION FOR GEO-HAZARDS

A Geographic Information System (GIS) platform was adopted in preparing the seismic hazard micro-zonation study for the GBA. In this study the objective was restricted to the ground motion amplification micro-zonation for the Greater Beirut Area, starting from the results of the analysis detailed above for max ground acceleration with 10% probability of exceedance in 50years.

Amplification of ground motion due to local soil conditions depends primarily on soil type, properties and thickness. Seed and Idriss (1982) presented approximate magnitudes of amplification for different soil types as a function of peak ground accelerations, indicating that most soils amplify peak acceleration where the firm ground acceleration is less than 0.1g, with the largest amplification occurring in "soft to medium stiff clay and sand". Idriss (1990) later improved the amplification curve for soft clay sites, based on additional analysis and data from the Mexico City and Loma Prieta events and showed that soft clay sites amplify peak accelerations up to 0.4g, beyond which "de-amplification" occurs as a result of the nonlinear behavior of soil under large strains.

The simplest method for producing a ground motion amplification map would be to map the distribution of soil type, soil thickness and rock exposures. Site-specific amplification factors could then be estimated from available amplification charts (Seed and Idriss, 1982). Zones would be mapped where the ground conditions correspond to soil categories for which distinctive patterns of ground response have been observed. Since in the Lebanese case in particular, surface motions are influenced primarily by the top 20 to 30 m of soil, the average shear wave velocity over this depth range is a reasonable indicator of amplification potential for mapping purposes. Therefore, mapping of the soil types with respect to their shear wave velocities, then assigning them appropriate ground motion amplification factors and multiplying these factors by the peak ground accelerations on bedrock would result in a map showing the amplified or de-amplified surface ground accelerations.

Data Collection and Manipulation

The mandatory starting point for a GIS-based micro-zonation study for the GBA was clearly the collection of data pertaining to geology, soil properties, peak ground accelerations (PGA) on bedrock,

groundwater and topography. The collection of data was a tedious task given the absence of reliable information, properly compiled and/or digitized. The collected data came from different sources, relatively old hard copy maps and other contributors. A summary of some of the relevant data coverages generated and a description of the processes involved in their inception is presented herein:

Soil Type Data

In 1955 a French geologist L Dubertret (1955) published a study commissioned by the ministry of public works, detailing the various geological formations in Lebanon. The report included geological maps for Lebanon which still form the basis of any subsequent mapping efforts. Other sources of data related to soil and rock nature and properties were screened, compiled and rigorously evaluated for inclusion in our GIS base map. They included previous studies related to the geotechnical characteristics of various soils/rocks in the GBA, particularly one by Ghannam (1987). Furthermore, we relied on geologic maps prepared for various government projects and which offered greater local scale definition, along with a very large number of site investigation reports and drilling records obtained from various ministries and local consulting and contracting firms involving work over the last 50 years in the GBA. An additional resource was the wealth of testing data compiled over the past four decades in the soil mechanics laboratories at the American University of Beirut. All the above-referenced sources resulted in a digital geotechnical base map indicating the presence of nineteen significant geological formations in the GBA which was developed at a scale of 1:20,000 (Bedran, 1997). Despite all the effort invested and the reliance on the significant contribution and effort by others, the level of reliability of this data is still quite variable. Notwithstanding the above limitations, the resulting map provides the most detailed geo-representation of the GBA showing the soil and rock formations along with their corresponding properties. The map presented in Figure 8 was used as the base on which the seismic micro-zonation study would be built.

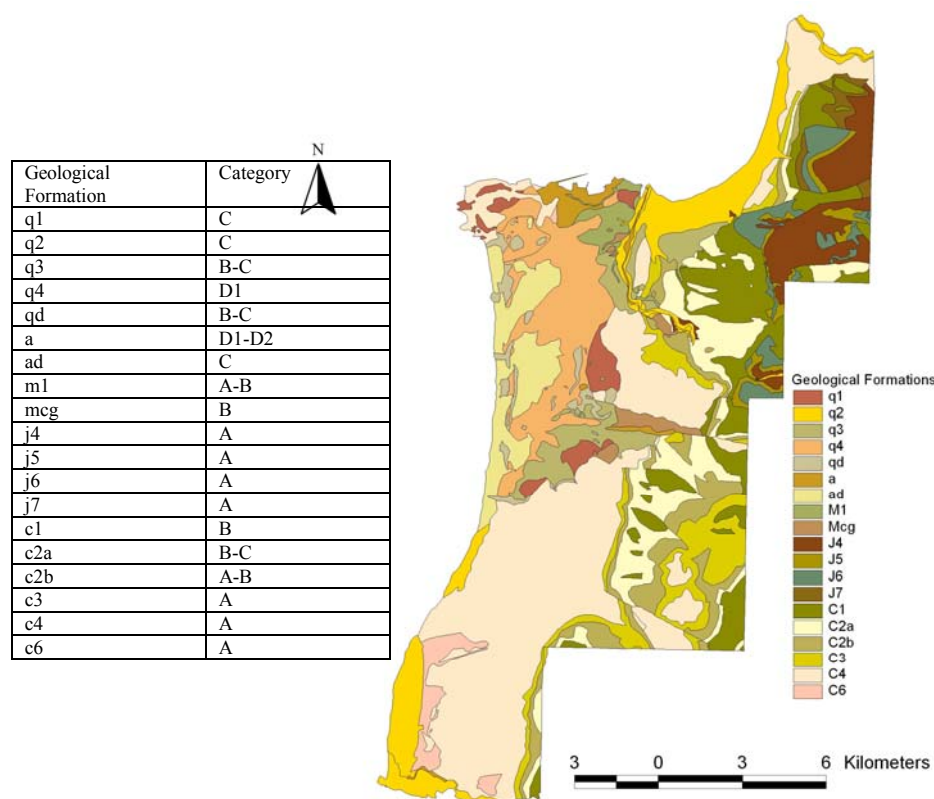


Figure 8. Geological formations within the GBA

Ground Amplification Maps

The ability of soils to transmit/amplify earthquake motion is a function of their shear wave velocity, among other parameters. In the case of the GBA, a direct measure of the shear wave velocities of the

different soils/rock deposits is not available. As such, the different units were categorized using Table 1 and based on their general classification (Finn, 1993).

Table 1. Categories for Soil Susceptibility to Amplification

Soil Category	General Description	Soil Category Definition	Susceptibility Rating
A	Competent/hard rock	$V_{ave} > 750$ m/sec	Nil
B	Deep cohesionless soils, stiff cohesive soils or mix of cohesionless with stiff cohesive soils, not soft clay	$360 \text{ m/sec} < V_{ave} < 760 \text{ m/sec}$	Low
C	Sands, silts and/or stiff/very stiff clays, some gravels; soft clay thickness < 3 m.	$180 \text{ m/sec} < V_{ave} < 360 \text{ m/sec}$	Moderate
D ₁	Profile containing a small to moderate total thickness (H_c) of soft to medium stiff clay	$V_{ave} < 180$ m/sec, and/or $3 \text{ m} < H_c < 15 \text{ m}$	High
D ₂	Profile containing a large total thickness, (H_c) of soft/medium stiff clay.	$V_{ave} < 180 \text{ m/sec}$, and/or $15 \text{ m} < H_c < 35 \text{ m}$	High
E ₁	Peats or highly organic clays,	$H_p > 3 \text{ m}$	Very High
E ₂	Very high plasticity clays	$H_{cp} > 7 \text{ m}$ and $PI < 75\%$	Very High
E ₃	Very thick soft/medium stiff clays	$H_c > 35 \text{ m}$	Very High

Notes:

- Soft/medium stiff clays are those with normalized, average shear wave velocities less than 150m/sec.
- Soils classification terms are those in the Canadian Foundation Engineering Manual, Third Edition.

Accordingly, the susceptibility to amplification for every type of soil formation found in the GBA was determined and is presented in Table 2 and graphically illustrated in Figure 9. From the table, it can be seen that certain formations are assigned a range of categories; for producing the map, the more conservative soil category is used, i.e., the one indicating higher susceptibility. As noted, this map provides a qualitative estimate of the soil susceptibility to amplification.

As expected, the areas where the soil consists of loose soft weak sands and silty clayey sands are the ones where the susceptibility to amplification is the highest. In order to get a quantitative estimate of the amount of amplification that every soil is capable of producing, Table 2, which is also based on Finn (1993), assigns an amplification factor for every soil category. This factor is multiplied by the PGA on bedrock from Figure 6, in order to produce the amplified ground acceleration at the surface. The results are presented in Figure 10. The results indicate that, in some areas, the peak ground accelerations may be amplified up to $\sim 0.35g$.

Table 2. Amplification Factors

Soil Susceptibility Category ^a	Shaking Intensity ^b pga				
	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g
A	1.0	1.0	1.0	1.0	1.0
B	1.2	1.2	1.1	1.0	1.0
C	1.6	1.4	1.2	1.1	1.0
D ₁	2.5	1.7	1.2	0.9	0.9
D ₂	2.0	1.6	1.2	0.9	0.9
E ₁ -E ₃	$1.2 \times D_1$	$1.2 \times D_2$	$1.2 \times D_1$	$1.2 \times D_1$	$1.2 \times D_1$

^aSee Table 2 for descriptions of soil susceptibility categories.

^bPeak surface horizontal firm ground acceleration from seismic hazard analysis.

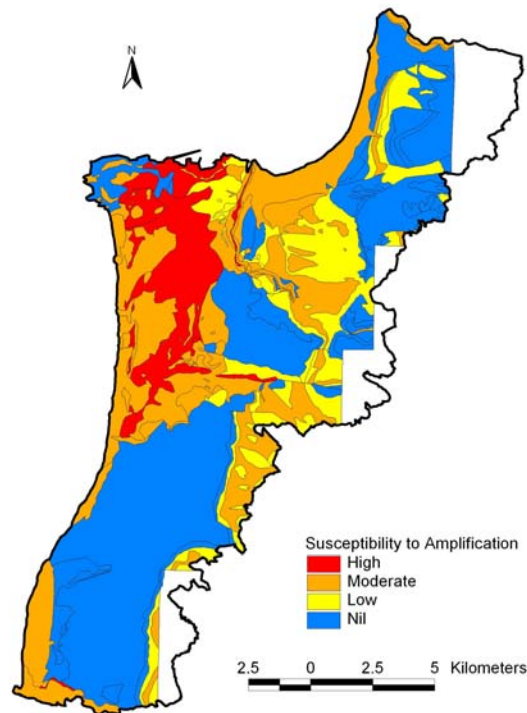


Figure 9. Susceptibility to amplification map

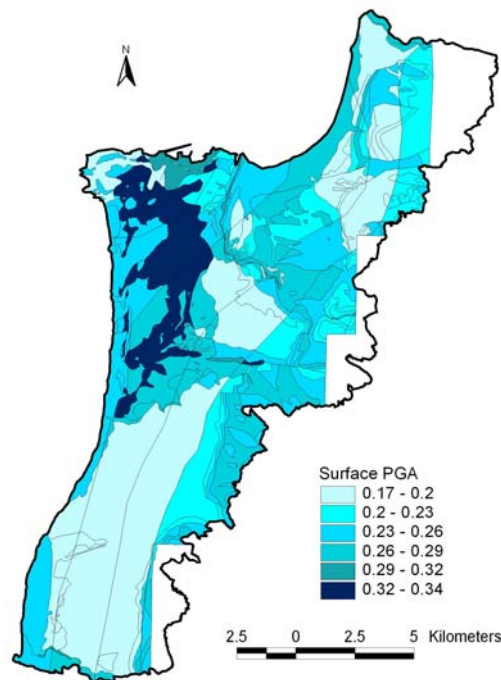


Figure 10. Amplified surface peak ground accelerations

CONCLUSIONS

This study concentrated on the evaluation of the seismic hazard of Lebanon to determine the most probable ground acceleration needed for seismic design. The seismic hazard evaluation was conducted using available methods of probabilistic seismic hazard analysis.

The results of the updated seismic hazard analysis for the Lebanon allowed the development of a seismic micro-zonation study for the Greater Beirut Area. Hazard maps were generated and produced in a GIS context. Given the absence of digitized records, the data used in our analysis was generated as part of this and other recent work. We believe that significant efforts should be directed at improving the quality and quantity of the data.

The generated amplified ground acceleration maps for the GBA suggest that areas previously considered of “moderate seismic risk”, should be revised to higher PGAs. Other geo-hazards such as liquefaction susceptibility and seismic slope instability may now be revised and developed and zoned based on the updated maximum ground acceleration data obtained from the seismic hazard study.

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