Seismic Hazard Analysis and Development of Ground Motion Parameters for Makkah Region in Saudi Arabia

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SUMMARY:
Recently, the Saudi government initiated a development plan involving the investment of nearly 33 billion U.S. dollars to transform Makkah city which hostess the most spiritual structures to Muslims, Al-Masjid Al-Haram and The Kabaa, into a city with world class facilities and services. These facilities and services include expanding the existing Masjid and constructing many high-rise hotels, hospitals and multi-story parking structures around the Masjid. Such heavy construction activities required conducting many seismic hazard studies to assess the level of seismicity within this area in order to develop seismic criteria that can be utilized for designing those new structures.

This paper presents the results of a study that was performed to assess the seismic hazard and to develop criteria for ground motion at Makkah city based on both deterministic and probabilistic approaches. The study involved; 1) Reviewing the geology and tectonic setting of Makkah area and its surroundings; 2) Compiling an earthquake catalogue, listing both historical and instrumental events occurred in nearby vicinity; 3) Defining the seismic source zones and their associated magnitude recurrence parameters; and 4) Finally, carrying out an assessment to the seismic hazard based on attenuation relationships. The obtained results from this study were in the form of peak ground motions and uniform hazard response spectra for this area. These results were compared with design values typically used for seismic design purpose within Makkah region.

Based on this study, it was concluded that most of the seismic activities (75%) affecting Makkah site are located along the main axial trough of the Red sea, whereas the remaining 25% occur at inland areas. Also, the study showed that based on deterministic approach that the maximum expected ground motion in Makkah area is ranging between 0.073g and 0.084g , while probabilistic study yielded maximum ground acceleration for probability of being exceeded 10% and life time ranges from 50 to 100 years ranging between 0.08g and 0.099g.

Keywords: Seismic hazard, Strong ground motion, Saudi Arabia, Response spectra.

1. INTRODUCTION

Makkah city is located in the middle of the western part of the kingdom of Saudi Arabia within an area called the Arabian shield (longitude 39.826°E and latitude 21.43°N). It is a part of Al Hejaz hill which extends in parallel lines with the red sea from the borders of the Kingdom till Al-sarwat Mountains in the South. It is bordered from the North by Al Medina region, from the East by Riyadh region, from the south by the regions of Abha and from the West by the Red Sea as shown on Fig.1.

Makkah region has been considered in the past by many research studies as an area of low or no seismicity. For instance, Ashour & Abdel-Rahman (1994) suggested that the maximum ground motion within Makkah region is 0.05g, while Al Haddad *et al.* (1994) and UBC (1997) classified Makkah as zone 0 with no seismic activity. However, recent studies by Al-Amri (2005) indicated that there is a possibility for occurrence of seismic events that is adequate to pose threat to the structures constructed within the city from nearby faults. Therefore, a seismic hazard assessment has been taken in this study to determine seismic ground motion parameters for seismic design of facilities and services within this area.

2. GEOLOGY, TECTONICS AND SEISMICITY OF MAKKAH ZONE

The Arabian shield, where the study area is located, is thought to be originated and formed of five Precambrian terranes. Probably, it had split away from the African shield along the rifts of the Red Sea and the Gulf of Aden during more than two episodes of sea floor spreading pre-early Miocene and post-Miocene rifts time. It is an ancient land mass with a trapezoidal shape and area of about 770,000 km^2. Its slightly-arched surface is a peneplain sloping very gently toward the north, northeast, and east. The framework of the shield is composed of Precambrian rocks and metamorphosed sedimentary and intruded by granites. The fold-fault pattern of the shield, together with some stratigraphic relationships suggests that the shield have undergone two orogenic cycles (Johnson and Kattan 2008).

Figure 1. Geographical location of Makkah

Tectonically the study area is dominated by the Ad Damm fault zone, which cuts diagonally across the area from northeast to southwest and divides the area into two contrasted structural domains. The southern structural domain is characterized by north-south striking foliation surfaces and south-plunging folds and lineations. The northern structural domain is characterized by northeasterly trends of the type that characterize the Jeddah terrane between Ad Damm fault and the Labunah thrust (Al-Saud, 2008). Several structural elements can be identified within the studied region as shown on Fig.2.

Examining figure 2 and figure 3 which shows the faults around Makkah area indicated that faults in this quadrants region can be divided into three categories. The first group is the thrust faults which are abundant around the Ad Damm fault and Al Ta'if area and had been the source of many minor earthquakes in the past. The second group is the Red Sea Faults which trended to NNW and belong to the main structural elements of the Red Sea system. These faults were initiated during the diversion of the Red Sea and they are high – angle normal faults, which generally deepen steeply toward the NE-SW direction. The final group is the Transform faults which trended to NNE and NE directions, and considered the main structural elements of Red Sea rift. Their trends are perpendicular to the rift axes. Belonging to this group of faults are, Ad Damm, Hawrah, Ash Shafa, WASF, and Fatima Faults.

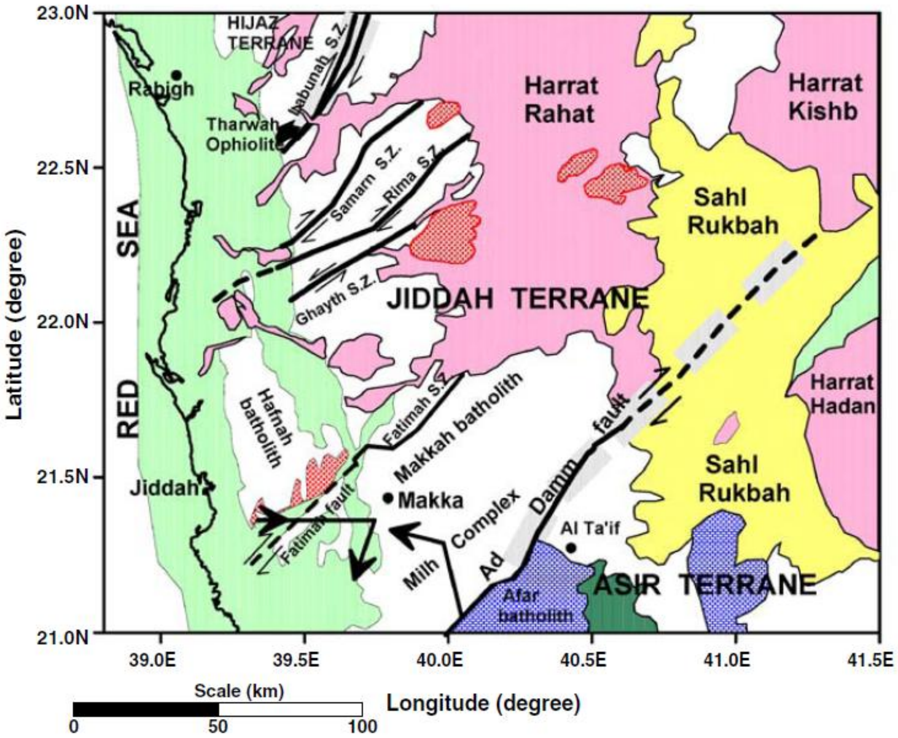

Figure 2. The main tectonic elements within the study area

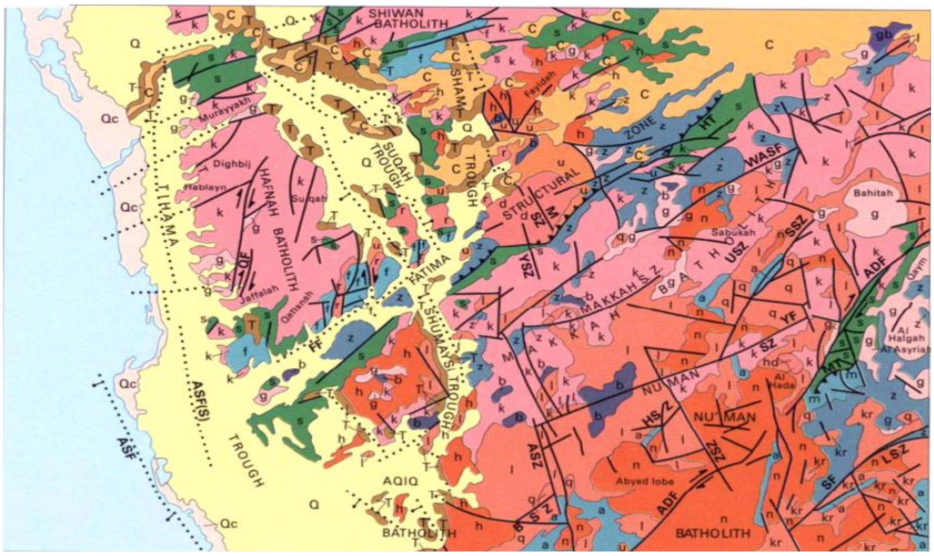

Figure 3. Faults around Makkah region

In addition, volcanic activity near Makkah can be noted. It includes Harrats Rahart, Kishb, and Hidan which resulted from recent basaltic volcanic eruptions formed contemporaneously with Red Sea rifting. They constitute one of the largest alkali basalt provinces all over the world, with an approximate area of 180.000 Km^2.

Seismically, Makkah region and surrounding area was subjected to many earthquakes that have a magnitude ranged from 3 to 6.9 on Richter scale. Prior to 1964 most of the earthquakes known within Makkah region were derived from surveying the available historical literatures. Documents indicated that on 859, 1121, 1191,1269, 1408 ,1630 and 1710 A.D strong earthquakes were felt in Makkah. The strongest was on 1121 A.D (assessed to have a magnitude of 12 on Mercalli scale) and resulted in damaging the Yemani corner of Al-Kabba. After 1964 seismic stations were introduce to KSA, and many earthquakes were instrumentally recorded. Most of these earthquakes occurred within the Red Sea fault at about 150 Km away from Makkah towards the west and south west directions as shown on Fig.4. As can be noted, there are two main sources for these earthquakes. The first main source is the Red Sea fault and it is characterized by the high seismic activities in terms of recurrence, magnitude and number. The second source is attributed to the structural zones within the Arabian shield, where most of the earthquakes occurred along or close to those inland faults. Also, it should be noted that the earthquake initiated from the Red Sea fault has the nature of forming earthquake swarms.

3. EARTHQUAKE CATALOGUE CLEAN UP AND COMPLETENESS

For this study, all available seismic events either historically reported or instrumentally recorded within a circle of a radius 300 km from Makkah area were collected. Four different seismological sources (catalogues) were utilized for compiling these data. These mainly include: The data base for Seismic Studies Center, King Saud University (SAED, 2003), The International Seismological Center (ISC, 2009), The European-Mediterranean Seismological center (EMSC-CSEM 2009), and The USGS National Earthquake Information Center (NEIC, 2009). This catalogue was assembled and cleaned from heterogeneities. Examining the data revealed that ; 1) Most of the earthquakes with high magnitude ($M \geq 3$) are initiated mainly from the Red Sea and represented about 60% of the total earthquakes recorded within the study area; 2) Most of the earthquake of small magnitude ($M<3$), were inter-plate earthquakes initiated mainly within the Arabian shield and these earthquakes represent about 33% of the total earthquakes recorded within the study area; 3) As long as we move towards the east in the kingdom, the earthquake epicenters decrease in number. Consequently, it can be concluded that Makkah is a region of moderate seismicity, since large earthquakes affecting this region is generated from faults located about 150 km far away inside the Red Sea, while the closest earthquakes are of small magnitude.

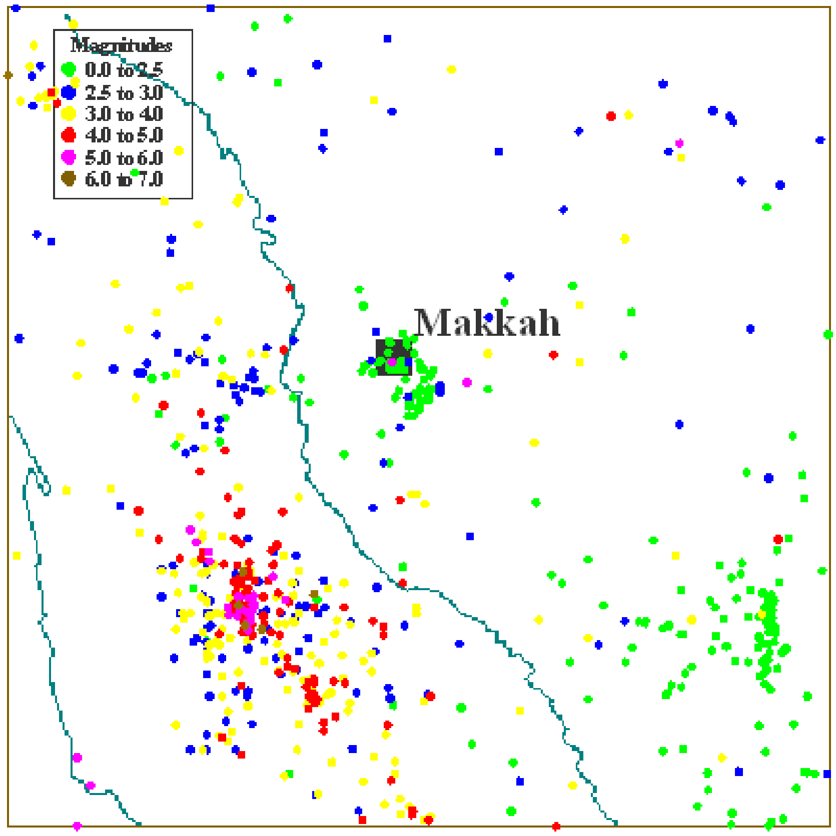

Figure 4. Seismicity map for the Makkah region and its vicinity

4. SEISMIC HAZARD ASSESSMENT

4.1. Modelling of Seismic Source Zones

Generally, there are several types of seismic source modelling; mainly point source, line or plane source and area source. In this investigation area source region model is adopted and assumed to have homogenous seismicity. For deterministic study, as shown on Fig.5, the seismic sources taken into consideration are four zones. Zone 1 which includes all the activities that occur within the Red sea to the south west of Makkah. The earthquake activity of this regional zone is relatively distant from the present local studying region, but includes many moderate events with magnitude M>4 occurred along the transform faults of the Red Sea, Which may be a result of the spreading and tectonic activity of the Red Sea rift trended NW-SE Parallel to the Red Sea rift axes. Zone 2 which include the seismic activities of Nu'man-Makkah-Fattima faulting system that is close to Makkah. The epicentre distribution map (Fig.5) shows that the activity of this zone is relatively low, but considered the most active one within the area of study due to its closeness. Zone 3 which are called Jeddah-Red Sea seismic Zone and extend along the middle Red Sea, and the activity continuous toward the middle part of the Red Sea, crossing its transform faults. This Zone includes many clustered small to moderate events. Most of these events with M>3 occurred along the transform faults of the Red Sea, which may be a result of the opening and tectonic activity of the Red Sea rift. Zone 4 that is located south of Makkah region along the Al-Damm fault. Seismic activity of this faulting system is moderate and clustered in some parts.

For probabilistic study, the four zones were extended into nine zones, to increase the accuracy of the performed analysis. Six of these sources are located in the Red sea, while the other three are located in land as shown on Fig.6.Seismogenic zoning selection in this case was carried out on the basis of a balanced combination of both geological and seismological information and based on examining the distribution of the earthquakes and studying the tectonic and geological setting.

4.2. Modelling of Seismic Source Zones

For the deterministic analysis, as previously indicated, two categories of seismic sources were identified, namely, the Red Sea source and the Inter-plate source. To determine the earthquake recurrence relationships from these two sources, the data were arranged in ascending order of magnitude and summed to determine the number of earthquakes in each magnitude range. The magnitude intervals were taken to be 0.2. Then, Gutenberg-Richter model (Gutenberg and Richter, 1954) was applied to this data. According to this model the cumulative frequency-magnitude relationship can be represented as:

$$\text{Log } N(M) = a - b\,M \qquad (4.1)$$

where, N is the total number of events having magnitude greater than M, M is the earthquake magnitude, a is the seismicity index parameter and b is the parameter related to applied stress. In this study, this relationship was utilized due to; 1) There is zero number of events in some magnitude intervals; and 2) The cumulative number of events is directly given by the observed data.

The best fit was selected as the most representative cumulative frequency-magnitude relationship for each observation period in each seismogenic source zone. Table 4.1 lists the computed values of the seismicity parameters as determined from analyzing the collected data. These values are considered reasonable for the purpose of this study and are comparable with the values obtained in previous studies (Al-Amri, 2004). It worth to mention here, that when these values were plotted a steeper change of slope was observed to occur within the higher magnitude classes and lower slopes for the lower magnitude classes. Such pattern is typical for regions of moderate seismicity.

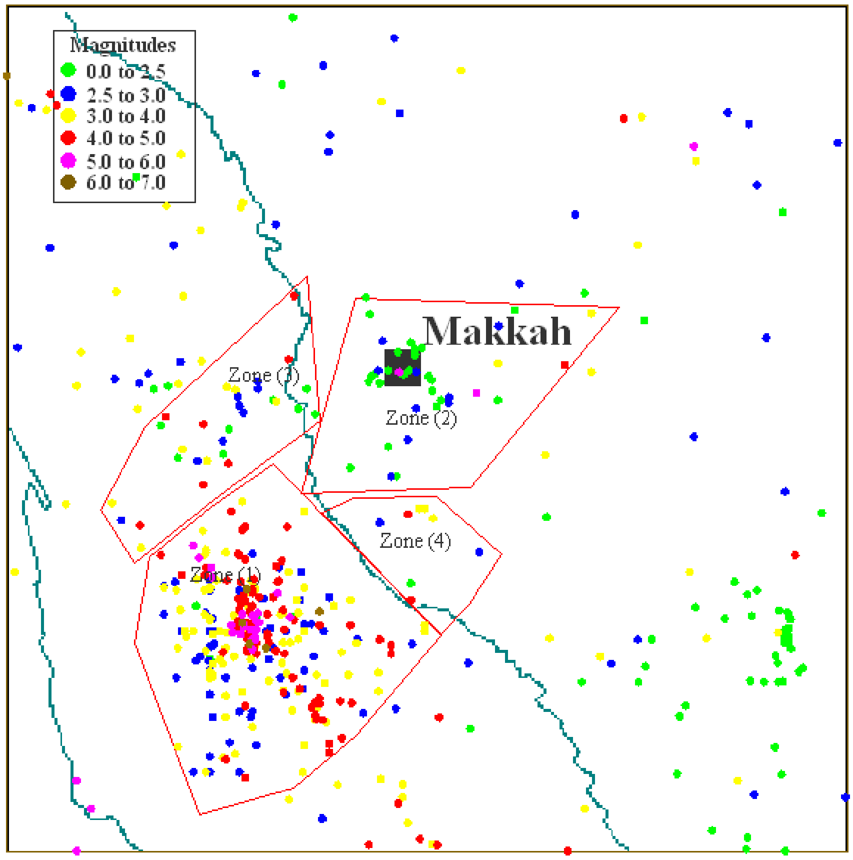

Figure 5. Seismic source zones for deterministic study

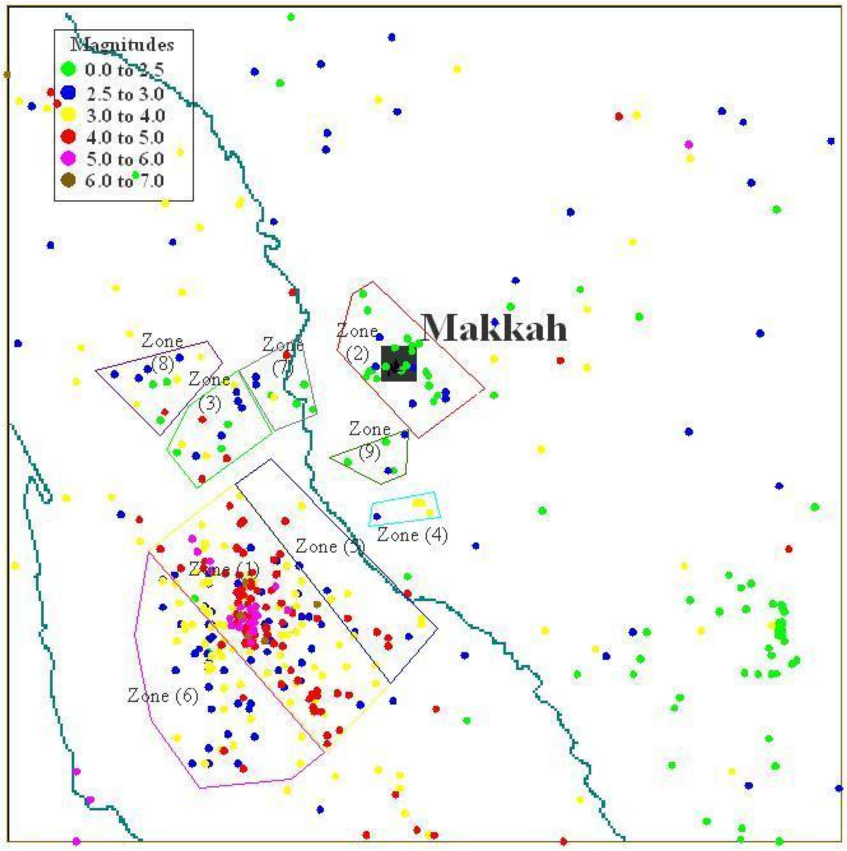

Figure 6. Seismic source zones for probabilistic study

Table 4.1. Parameters of the frequency-magnitude relationship

Zone No.	Name	Seismicity Parameters	
		a	b
1	Red Sea Zone	3.570	0.436
2	Inter-plate (Makkah zone)	3.112	0.528
3	Both zones combined together	3.759	0.470

For the probabilistic study, the values of a-values and b-values were computed for each region based on events extracted from the catalogues. Table 4.2 lists the computed values for each seismogenic zone considered in the analysis, in addition, to reporting the maximum and minimum magnitudes recorded within each zone.

One of the important element in seismic hazard assessment is the attenuation relationship which defines the reduction in peak ground acceleration (PGA) or intensity (I) with distance from the epicentre (R) for an earthquake of given magnitude. There are several factors that affect the attenuation relationship such as 1) damping of transmitting media; 2) magnitude of earthquake; 3) type of fault rupture mechanism; 4) distance of site from earthquake hypocenter; and 5) soil characteristics of the site. For this study, the Makropolus relationship for attenuation recommended by (Al Amri 2005) was utilized. According to this relationship, the peak horizontal acceleration attenuation in terms of body wave magnitude is introduced as follows:

$$Ln (A) = 0.7M_b - 1.8 Ln (R+25) + 7.68 \quad (4.2)$$

where, A is the peak horizontal acceleration in gals (cm/sec2), Mb is body wave magnitude and R is the distance between epicenter and the site (Km).

Table 4.2. Parameters of the frequency-magnitude relationship

Name	Seismicity Parameters		$M_b$max	$M_b$min
	a	b		
Zone 1	3.0154	0.3354	6.7	1.0
Zone 2	1.729	0.3479	3.0	1.0
Zone 3	1.720	0.3218	4.3	1.0
Zone 4	0.9758	0.1628	3.3	1.0
Zone 5	1.5676	0.2158	4.5	1.0
Zone 6	2.6179	0.4486	4.0	1.0
Zone 7	1.3995	0.3538	3.2	1.0
Zone 8	1.5672	0.3112	3.8	1.0
Zone 9	1.0708	0.2644	2.6	1.0

4.3. Deterministic Approach

In order to convert from magnitude to ground motion parameters, many relationships were previously utilized. Krinitzky et al (1988) adopted the following equations for faults having focal depth less than 19 km and hard sites. The peak ground accelerations, velocity and duration for hard sites are expressed as follows:

$$A = [10^{(1.23+0.385M-0.00255 R-\log R)}] / 981 \quad (4.3)$$

$$V = 10^{(-0.67+0.489M-0.00256 R-\log R)} \quad (4.4)$$

Where, A is the ground acceleration expressed in g's, Vis the velocity expressed in cm/s; and R is the distance from epicentre (km)≥ 10 Km. By applying these equations to the four seismo-tectonic zones selected for the deterministic study, the following results summarized in table 4.3 were obtained.

Table 4.3. Maximum **e**xpected seismic parameters

Seismic Source	Distance to site (Km)	Max Magnitude	Maximum PGA (g)	Velocity (cm/sec)
Zone 1	145	6.7	0.0193	1.185
Zone 2	18	4.8	0.0728	2.976
Zone 3	40	4.9	0.0270	1.091
Zone 4	54	4.0	0.0082	0.264

If Makropolus equation, previously recommended, is applied to these data, it will yield the values listed in table 4.4, which are comparable with those indicated in Table 4.3 for the same zone.

Table 4.4. Maximum PGA calculated based on Makropolus relationship

Seismic Source	Distance to site (Km)	Maximum Magnitude	Maximum PGA (g)
Zone 1	145	6.7	0.0232
Zone 2	18	4.8	0.0838
Zone 3	40	4.9	0.0384
Zone 4	54	4.0	0.0141

As can be noted from examining previous results, it is clear that zone 2, although expected to generate earthquakes of less magnitude than zone 1, due to its closeness to Makkah is expected to generate the highest peak ground acceleration which can reach up to 0.0838g.

4.4. Probabilistic Approach

In this study probabilistic seismic hazard analysis for the regions was performed using the computer code EQRISK (McGuire, 1976). Input parameters for EQRISK have been prepared and they consist of geometry of source zones, annual probability of being exceeded, rate of occurrence, Richter parameters, and coordinates of Al-Masjid Al-Haram as being the center of Makkah city. The output of the program was the anticipated peak ground acceleration with a 10% probability of being exceeded during time span of 50 and 100 and 200 years. The results indicated that the mean peak ground acceleration in terms of (g), for 10% probability of being exceeded and 50, 100 and 200 years life time are 0.0801, 0.099, and 0.131, respectively.

5. DISCUSSION OF THE RESULTS

From the previous analyses, it can be concluded that by applying the deterministic seismic hazard approach, the maximum earthquake hazard determined in terms of peak ground horizontal acceleration at site base rock ranged from 0.0728 to 0.0838 g (71.4 cm/sec2 to 82.2 cm/sec2) resulting from the occurrence of an earthquake with magnitude 4.8 at 18 Km away from Al-Masjid Al-Haram. In addition, the maximum expected accelerations calculated by the probabilistic approach for probability of being exceeded by 10% and life time ranging from 50 to 100 years ranged from 0.0801 to 0.099 g (78.57 cm/sec2 to 97.12 cm/sec2) which are comparable to the values obtained by deterministic approach.

To develop the required site response spectra, a series of international real time histories for earthquakes recorded on firm soil (with high a/v ratio) we utilized by scaling their peak accelerations to 0.099g and develop the corresponding response spectra's for 5% damping. The selected earthquakes are Park field 1960 (designated as H1), San Francisco 1957 (designated As H3), Helena arc 1935 (designated as H5), Lytle creek earthquake 1970 (designated as H6), San Fernando earthquake 1971 (designated as H8) and Monte Negro earthquake 1979 (designated as H14). The response spectra for the scaled earthquakes were shown on Fig.7, for 5% damping. Also shown on the same figure is the average design response spectrum for these spectra, designated as Hav.

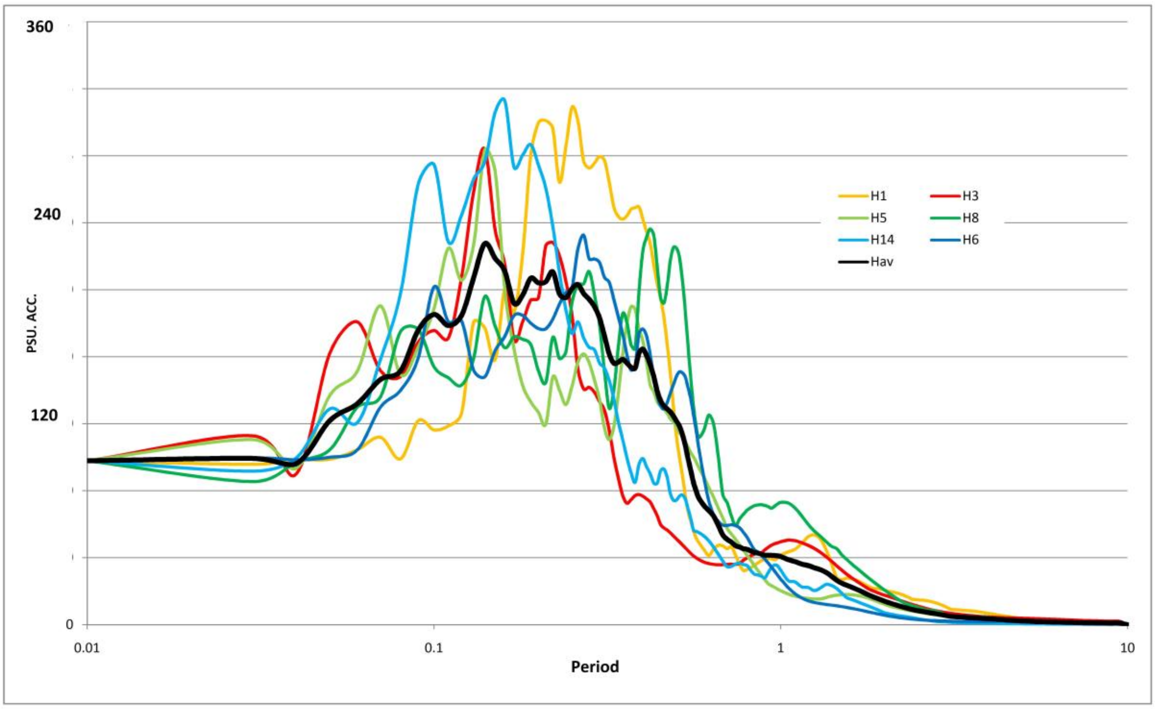

Figure 7. Response spectra for the selected earthquakes

It worth to mention here, that comparing these results with code requirements for ICBO (1997) which is widely used for designing buildings in Makkah, indicated that this region should be classified as zone 1 for buildings with short life time (50 years or less), and as Zone 2A for important building with life time 100 year and not as traditionally utilized zone 0. Also, comparing these results to SBC 301(2007) which is the new Saudi Building Code indicated that S_1 for Makkah area which is the mapped maximum considered earthquake response acceleration is 0.064g which is comparable with the finding of this study, but on the low side. On the other hands, the mapped maximum considered earthquake spectral response acceleration at short periods is 0.182 g which is comparable with the average value of 0.2g extracted from the average design spectra shown on Fig.7.

6. CONCLUSION

This paper investigated the seismic hazard and seismic zoning for Makkah region and its surroundings based on both deterministic and probabilistic approach. The results of this study indicated that, although this area is of low seismicity, moderate seismic events can occur and threaten the existing structures within the area. The PGA within this region was estimated to be ranging between 0.073g to 0.099g. These values indicated that structures within this area should be designed for zone 2A according to the UBC 1997. Furthermore, they indicated that , although the current Saudi Building code, SBC 301 offers a good estimate for seismic activity within this area, it is still underestimate the PGA for this area.

It worth to mention here, that beside the inherent uncertainties in seismic hazard assessment, the results obtained in this study have some other limitations and therefore future research in some key areas is needed as; 1) the hazard assessment is done for ideal bed-rock condition, therefore care should be taken when using the results for sites with special local conditions; and 2) The attenuation relation used in this investigation is derived internationally, and attenuation relations for this region should be developed based on the recorded strong motion data.

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