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# Seismic Hazard Assessment and Local Site Effects on United Arab Emirates major Cities and their environs: An Overview

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## *Abstract*

This paper summarizes the results of seismic hazard assessment of the United Arab Emirates (UAE) and the influence of local site effects on the intensities of ground shaking on recently emerged mega projects in UAE major cities including Abu Dhabi, Dubai, Sharjah and their localities. The probabilistic seismic hazard assessment was based on: (1) recently developed new generation of ground motion prediction equations; (2) collection of catalogues of various degrees of completeness that were homogenized for temporal distribution of events; (3) source zones that were delineated based on their seismic activities and tectonics; and (4) activity parameters that were based on doubly bounded magnitude-frequency relationships. The local site effect is based on selected time histories that were chosen based on a target response spectrum. This target response was obtained from the results of the probabilistic seismic hazard assessment stated above. In addition, subsurface geotechnical data from several different sites were used to evaluate the effect of local site conditions on ground response during earthquake. Dynamic properties of soil for selected soil profiles have been generated and one-dimensional site response analysis has been conducted. Results are presented in terms of response spectral accelerations (RSA) with a breakdown of their range ($S_{0.2}$ and $S_1$) for different site classes, representative hazard spectra, de-aggregation and development of site amplification factors for Dubai-Sharjah and their environs.

*Keywords: Seismic Hazard Assessment; Response Spectral Accelerations; Hazard Spectra; Site Amplification factors.*

## 1. Introduction

United Arab Emirates (UAE) is located in the southeastern corner of the Arabian Peninsula on the Arabian Gulf covering an area of approximately 83,600 km$^2$. The country comprises of seven emirates with Abu Dhabi being the capital. The spatial distribution of the seven emirates is shown in Fig. 1(a). Although Abu Dhabi has a large area, the majority of the infrastructure is located in the northern region of Abu Dhabi. Even in other major cities such as Sharjah, Dubai and Ajman, the developed area is relatively small, and covers the western side of these emirates bordering the Arabian Gulf. The Arabian Peninsula is not considered as seismically active. However, recent shakings of the neighboring areas such as Oman and Dibba have raised the awareness of a potential hazard to UAE [1-3].

In recent years, UAE major cities have experienced significant urban development and an unprecedented boom in its construction industry that resulted in many mega projects including Burj Khalifa – the world tallest building. This massive development coincidentally coupled with recent increase in seismic activities in the nearby Zagros Fold and Thrust Belt and the distant Makran Subduction Zone. Such events alerted government building authorities and building designers to pay more attention to the seismic effect and seismic risk on such mega projects. These unprecedented activities also alerted authorities to seriously consider seismic effect on designing new buildings. Therefore, investigation of seismic response becomes necessary.

Specifically, this paper will present a summary of results of seismic hazard maps for UAE, spectral accelerations with a breakdown of their range ($S_{0.2}$ and $S_1$), representative hazard spectra, de-aggregation and development of site amplification factors for Dubai-Sharjah and their environs. This study will contribute to the elements of generating the specific parameters needed for developing seismic design code for UAE.

## 2. Previous Studies

Several researchers have conducted probabilistic seismic hazard studies of UAE and its vicinity [4-12]. The results of their study, which were based on probability of exceedance ranging from 10% to 2% in 50 years, showed large variability in the Peak ground Acceleration (PGA). The PGA of these studies ranged between 0.05g and 0.32g. The variability in these results has been attributed to many factors that include use of different source model, activity parameters based on developing catalogue of events, catalogues and different ground motion prediction equations, among others. To improve on these results the authors conducted a comprehensive seismic hazard assessment of UAE [13-15]. The seismic hazard assessment conducted was based on the use of a homogenized catalogue of various degrees of completeness for temporal distribution of events (Surface magnitudes, Ms), activity parameters that are based on double bounded magnitude-frequency relationships, modified zonation of area sources, and next generation of ground motion prediction equations. The result of this study will be summarized in subsequent sections. This study provided seismic hazard values for all parts of UAE including hazard curves, values of PGA, spectral accelerations at 0.2s and 1s ($S_{0.2}$ and $S_1$), Uniform Hazard Spectra (UHS), and de-aggregation of seismic hazard. The results were generally provided in conformance to and compliance with the provisions given in most modern building codes such as the International Building Code (IBC 2012) and Eurocode 8. Moreover, several researchers conducted site response analysis for some limited cities within UAE [13, 16-19].

Balwan [16] performed site response analyses for Sharjah using data from several boreholes logs, and equivalent linear method to account for the nonlinearity of the soil deposit [20]. He used a single acceleration time history for all sites which is a major drawback of this study. The study provided zonation maps of PGA for Sharjah taking into consideration the amplification potential. Spectral acceleration at different periods was not considered in assessing the amplification potential of Sharjah.

Ansal et al. [17] used different borehole logs data, performed site response analyses and developed microzonation maps for local site effect for Dubai depicting amplification factors. The selected and scaled time histories they used did not exactly represent the hazard spectra for the sites [15], in addition they used damping ratio and shear modulus degradation curves that have been shown to create significant offset in the results. To improve on these results the authors conducted a comprehensive local site effect study for the three major cities of UAE – mainly, Abu Dhabi, Dubai and Sharjah [13, 18-19]. The conducted local site effect study was based on a selected time histories that were chosen based on a target response spectrum. The target response spectrum was obtained from the results of the probabilistic seismic hazard assessment conducted by the authors as previously stated [13-15]. In addition, subsurface geotechnical data from several different sites were used to evaluate the effect of local site conditions on ground response during earthquake. Dynamic properties of soil for selected soil profiles were generated and one-dimensional site response analysis was conducted.

Other seismic studies were conducted by several researchers [21-25]. Abdalla et al. [22] studied the vibration characteristics of a far-field earthquake and their shaking effects on Dubai emerging high-rise buildings. Their study concluded that UAE could be exposed to frequent large magnitude earthquakes generated from distant seismic source zone (Zagros fold–thrust belt) with dominant long-period content that may have damaging effect on Dubai rapidly increasing high-rise buildings.

Mwafy [23] conducted study to predict earthquake losses in the highly populated area of Dubai, UAE. He used satellite images and GIS data for generating the building inventory. A wide range of vulnerability relationships were prepared and integrated with a loss estimation system for the UAE. He concluded that the developed fragility curves confirmed the vulnerability of the buildings to severe distant seismic events, and highlight the pressing need for formulating earthquake loss assessment and mitigation strategy for this region.

Safak et al. [24] studied the effect of large and distance earthquake on Abu Dhabi's tall buildings. Some of the tall buildings were instrumented with real-time structural health monitoring systems that recorded a large earthquake (M=7.8) at a far distance (900 km) that occured on April 16, 2013. They found that, although the peak accelerations from such earthquake was low, however the key characteristics of the ground shaking and building response were: (1) very long duration of shaking; (2) concentration of ground motion energy at long periods; and (3) large amplitude resonant vibrations. They confirmed that large, distant earthquakes could create long-period, long-duration ground shaking in Abu Dhabi tall buildings.

Yagoub [25] investigated the spatio-temporal distribution of earthquake events taking place in UAE from 1984 to 2012 and their effect. He found that most earthquakes clustered in the Eastern part of UAE and almost 50% of the events during the study period took place on 2011. This corraborated with the USGS report that 2011 experienced highest earthquake activity in 20 years. He used GIS weighted overlay analysis to generate earthquake risk zones and a hazard map while taking into account several parameters from geology, soil, slope, land use, historical earthquake events, fault line, among others.

## 3. Geology, Tectonic setting and Seismicity of the Region

### 3.1 Geology

The geology of the United Arab Emirates and the Arabian Gulf area, has been substantially influenced by the deposition of marine sediments associated with numerous sea level changes during relatively recent geological time [26]. With the exception of mountainous regions shared with Oman in the north-east, the country is relatively flat. In general, UAE geology follows that of the Arabian Platform where the rocks have been accumulated on stable marine-to-fluviatile shelf. Repeated Uplift and collapse of arches and basins, movements on fault blocks, and migration of shoreline back and forward across this shelf resulted in the interactions and migrations of sandstones, siltstones, carbonates and salt basin that characterize the Phanerozoic of this region [9, 27-29]. Figure 1(b) shows the geology of UAE.

### 3.2 Regional Tectonic Setting

UAE is located on the Arabian plate which is regarded as seismically stable [30]. The tectonic setting on regional scale is depicted in Fig. 1(c). Significant crustal deformations and recorded seismic events are rare within the Arabian Peninsula [27]. Although the Arabian plate is bounded by many active tectonic boundaries, major contribution to the seismic hazard in UAE is from Zagros fold and thrust belt and Makran subduction zone. The Arabian plate is moving north at a rate of approximately 21 mm/year [31] and slight rotational movement also creates subduction zone at the boundary of Makran [26]. Movement of Arabian plate is also associated with the formation of Zagros fold and thrust belt in Iran that extends to the edge of the Persian Gulf [32]. In addition to Zagros and Makran regions, the active tectonic structures present in the Oman Mountains (Dibba fault) can also contribute significantly to the seismic hazard in UAE especially in the north and east of the country [33]. Most of the earthquakes in Zagros region are shallow earthquakes at an average depth of 15 km associated with blind thrust faults in the Precambrian metamorphic rocks [34]. The region has the potential to generate earthquakes with magnitude ($M_s$) larger than 7. The depths of earthquake foci tend to get deeper (40 km) towards the transition between Zagros and Makran regions. This transition creates complex faulting systems known as Zindan-Minab zone [35]. The Makran region itself is subducting at an estimated rate of approximately 25 mm/yr [31]. Oman Mountains towards the northeast of UAE exhibit active seismicity. Kusky et al. 2005 also reports historical seismicity associated with this Cretaceous Ophiolite Obsduction. Instrumented earthquake with magnitude greater than 5 has been recorded associated to this faulting mechanism. Recent studies associate this fault system (Dibba fault, Wadi Shimal, and Wadi Ham fault) as an extension of Zindab-Minab line. Since the seismic activity is not well documented for this source, rates of uplift and deformation rates shall be used to characterize the source.

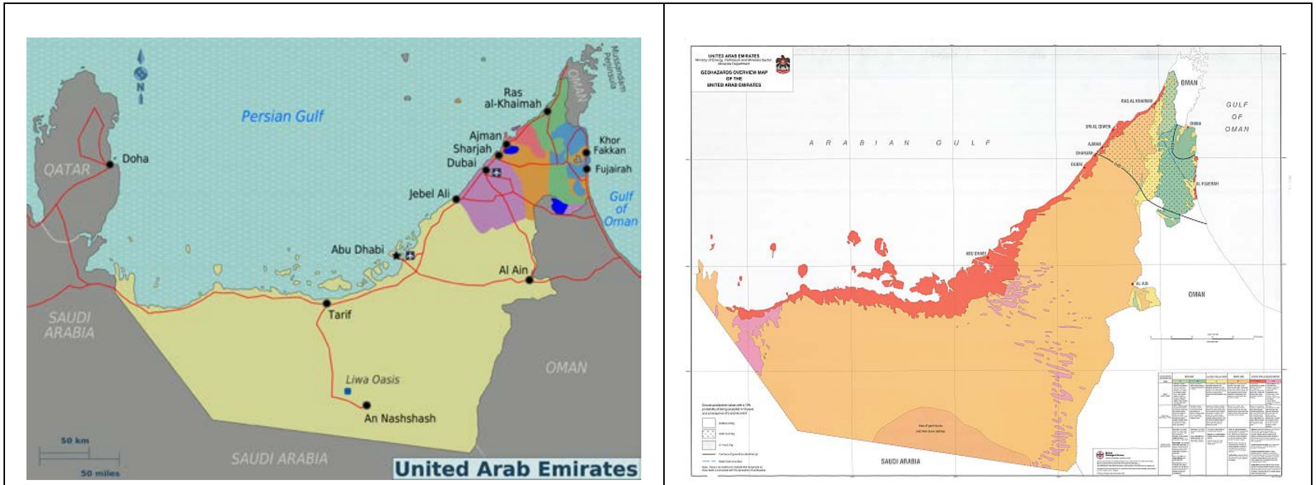
### 3.3 Regional Seismicity

Different databases from sources such as United States Geological Survey (USGS) and National Geosceinces of Iran were used to develop a seismic catalogue for the sources around UAE. The earthquake database from National Geoscience uses various references such as National Earthquake Information Center (NEIC) [36], International Seismological Center (ISC) [37], Ambraseys and Melville [38], Nowroozi [39], Nabavi [40], National Oceanic and Atmospheric Administration (NOAA) [41] among many others. Events with magnitude greater than four and between 1900 and 2010 were selected as the basis of catalogue to identify the sources. The catalogue was cleaned using standard protocols of removing duplicated events and aftershocks and for completeness using methods established methods. Historical records of earthquakes in the region were especially considered for Arabian Craton, Oman Mountains, and Makran region. Sources like Zargos and Zindam-Minab were characterized by instrumentally recorded data since 1910. The abundance of instrumented events was considered sufficient for defining the slope of Gutenberg Richter relationship which has significant effect on the outcome of Hazard. Historical events were given due consideration in selecting the upper bound magnitudes. Fig. 1(d) shows a regional seismicity that was recorded by Dubai Seismic Network from 2006 – 2014 (Bulletin of Dubai Seismic Network).

## 4. Probabilistic Seismic Hazard Assessment

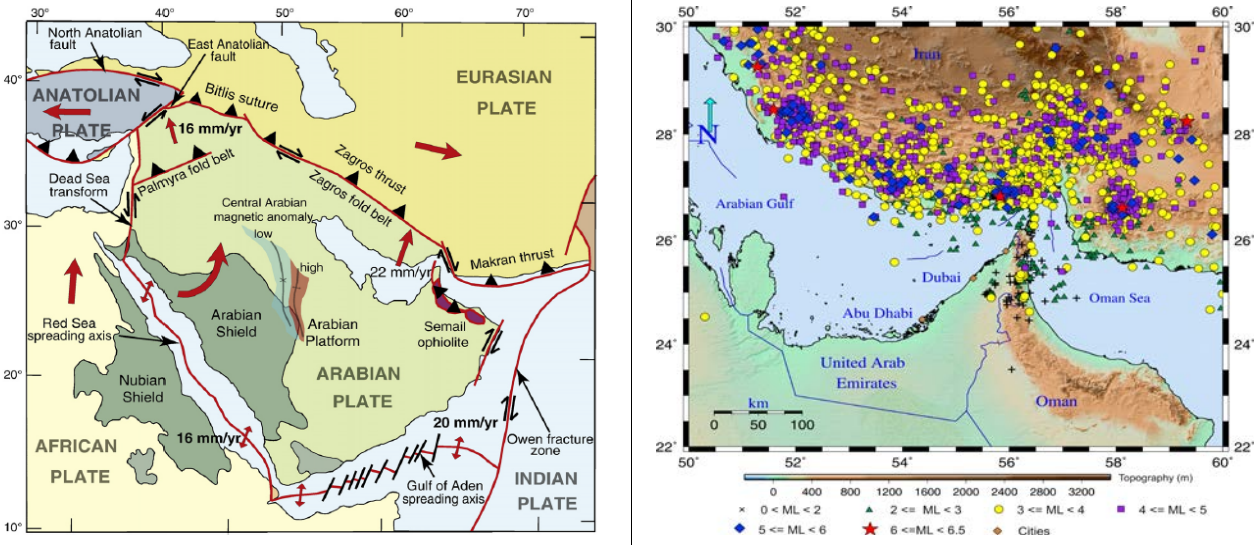
### 4.1 Earthquake catalogue and source model

Different databases from different sources including United States Geological Survey (USGS) and National Geosciences of Iran were used to develop a seismic earthquakes catalogue. To identify the earthquake sources, events with magnitude greater than four ($M_w > 4$) and dated between 1900 and 2010 were selected as the basis of catalogue. The catalogue was cleaned using standard protocols of removing aftershocks and duplicated events. For completeness the methods suggested by Knopoff [42] were used. Historical records of earthquakes in the region were especially considered and were given due consideration in selecting the upper bound magnitudes. The conversions of the magnitude scales were performed by using global conversion equations [43]. The development of seismic source model is based on the work of Aldama et al. [11]. Seven distinct seismic source models have been adopted. Details of the source model are given in [13-15].



(a) Geographic location of UAE
(Source: www.googlemaps.com)

(b) Geology of UAE
(Source: http://geospatial.com )



(c) Tectonic map of UAE surroundings
(Source: Stern and Johnson [44])

(d) Regional seismicity of UAE (2006-2014)
(Source: http://www.m1.ae/DSN.html)

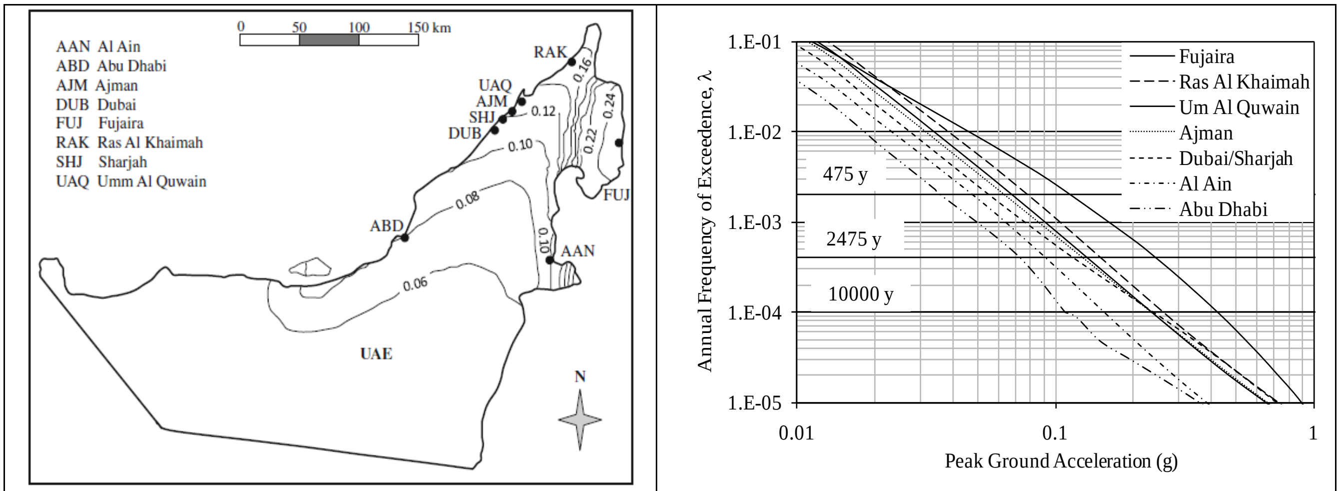
Fig. 1 – Geographic location, geology, tectonic and regional seismicity of UAE

## 4.2 Ground Motion Prediction Equations

Ground motion prediction equations (GMPEs), specific to UAE, are not available. All previous seismic hazard analysis performed for UAE used GMPEs developed for other geographical areas. The choice of these equations often is based on guidelines proposed by Cotton et al. [45]. Alternatively, equations (Next Generation Attenuation Equations) that were developed after the analysis of worldwide seismicity are increasingly being used. A total of seven different GMPEs [46-52] were used in this study including NGA equations. Most seismic sources were assigned at least two GMPEs equation. Three NGA equations of Boore and Atkinson [46], Abrahamson and Silva [47], Campbell and Bozorgnia [48] and one by Abrahamson and Silva [49] were assigned to the source zones of Zagros and the Oman Mountains. For the Makran region, the equations of Atkinson and Boore [50] and Youngs et al. [51] were used due to their suitability for earthquakes generated in subduction zones. The equation by Atkinson and Boore [52] was assigned to the Arabian Craton.

## 4.3 Seismic Hazard Assessment Results

The commercially available software EZFRISK (Risk Engineering Inc.) that is based on total probability theorem [54] was used. Figure 2(a), and (b) present the contours of mapped peak ground accelerations (PGA) for return period of 2475 years. Results presented in Fig. 2(a) indicate higher seismicity towards the east and northeast of the country with relatively little difference in seismicity level within the southern part (Emirate of Abu Dhabi). The seismic hazard along the western coast is generally dominated by the Zagros fold and thrust belt; whereas Oman Mountains contributed largely to the hazard on the eastern side. These results are in line with the general expectation of hazard distribution in UAE due to the presence of active sources towards the North and East. The contour maps of short and long period shaking generally follow the same trend as the contour map of PGA. Figure 2(b) shows seismic hazard curves (PGA) for all major cities of UAE.



(a) 2,475 years return period [15]

(b) Seismic hazard curves for UAE [15]

Fig. 2 – Mapped peak ground accelerations in units of “g”

## 4.4 De-aggregation of UHS spectra

Table 1 and Table 2 show the Peak Ground Acceleration (PGA) and spectral accelerations for major cities in UAE for return periods of 475 and 2475 years. The PGA for Ras Al Khaimah (R.A.K.), lying on the North Western boundary of UAE, is the largest amongst the Emirates. This is expected because R.A.K. is located closest to Zagros region as well as to Oman Mountains. The Zagros region was expected to be the potential hazard for UAE cities. However, PGA for Fujaira is the greatest. This is also expected because even though R.A.K. is closer to the Zagros region, the effect of Oman Mountains would have contributed to the hazard for Fujaira in addition to Zagros region.

Table 1 – Mapped spectral accelerations for major cities for return period of 475 years

| City | Latitudes | Longitudes | PGA (g) | 0.2s (g) | 1s (g) | 2s (g) | 3s (g) | 4s (g) |
|---|---|---|---|---|---|---|---|---|
| Abu Dhabi | 24.50 | 54.35 | 0.035 | 0.071 | 0.040 | 0.033 | 0.016 | 0.009 |
| Ajman | 25.42 | 55.50 | 0.055 | 0.140 | 0.058 | 0.033 | 0.020 | 0.012 |
| Dubai | 25.30 | 55.33 | 0.047 | 0.121 | 0.052 | 0.031 | 0.017 | 0.011 |
| Sharjah | 25.38 | 55.43 | 0.052 | 0.141 | 0.058 | 0.032 | 0.018 | 0.014 |
| Fujaira | 25.12 | 56.30 | 0.113 | 0.249 | 0.057 | 0.032 | 0.018 | 0.012 |
| R.A.K | 25.83 | 56.00 | 0.070 | 0.175 | 0.063 | 0.036 | 0.021 | 0.014 |
| Umm Al Quwain | 25.46 | 55.60 | 0.060 | 0.152 | 0.059 | 0.034 | 0.020 | 0.013 |
| Al-Ain | 24.23 | 55.75 | 0.038 | 0.088 | 0.045 | 0.030 | 0.021 | 0.012 |

Table 2 – Mapped spectral accelerations for major cities for return period of 2475 years

| City | Latitudes | Longitudes | PGA (g) | 0.2s (g) | 1s (g) | 2s (g) | 3s (g) | 4s (g) |
|---|---|---|---|---|---|---|---|---|
| Abu Dhabi | 24.50 | 54.35 | 0.073 | 0.178 | 0.075 | 0.045 | 0.025 | 0.017 |
| Ajman | 25.42 | 55.50 | 0.122 | 0.300 | 0.113 | 0.070 | 0.039 | 0.026 |
| Dubai | 25.30 | 55.33 | 0.118 | 0.251 | 0.100 | 0.055 | 0.030 | 0.020 |
| Sharjah | 25.38 | 55.43 | 0.120 | 0.285 | 0.109 | 0.068 | 0.037 | 0.025 |
| Fujaira | 25.12 | 56.30 | 0.250 | 0.565 | 0.131 | 0.073 | 0.040 | 0.028 |
| R.A.K | 25.83 | 56.00 | 0.154 | 0.356 | 0.126 | 0.074 | 0.041 | 0.028 |
| Umm Al Quwain | 25.46 | 55.60 | 0.144 | 0.314 | 0.118 | 0.071 | 0.040 | 0.027 |
| Al-Ain | 24.23 | 55.75 | 0.097 | 0.225 | 0.082 | 0.048 | 0.027 | 0.018 |

Figure 3 presents the degaggregation of PGA and $S_1$ for R.A.K. for a return period of 2475 years. The deaggregation of PGA suggests a dominant magnitude-distance scenario of 5 and 40 km. The deaggregation of $S_1$ suggests two probable scenarios. One scenario is for magnitude of 6 and distance of 40 km and the other with a magnitude of 6.75 and distance of 200 km. The time history analysis shall therefore consider both scenarios.

The deaggregation of hazard (PGA and $S_1$) for Dubai for a return period of 2475 years given in [14], indicates two possible magnitude-distance scenarios. The spectral matching of the UHS at long periods for Dubai should consider an earthquake with mean magnitude of 7 occurring at mean distance of 60 km and then at 300 km. The short and long distance earthquakes represent the events occurring in Zargos and Zindan-Minab transition respectively. As expected, contributions from larger earthquakes occurring at longer distances tend to contribute more with the increase in spectral period. For Dubai especially this contribution is expected from earthquakes occurring in Zindam-Minab transition fault and Makran subduction zone.

These deaggregations suggest that sites located in the south of UAE are affected by distant earthquakes and this distance increases with increase in spectral period. On the other hand the sites located in the North are influenced by earthquakes that are generated in nearby active zones and also by large earthquakes in distant zones such as Makran. The deaggregation for spectral period of 0.2s is not significantly different than the deaggregation for PGA at this return period (2475 years) and is therefore not included.

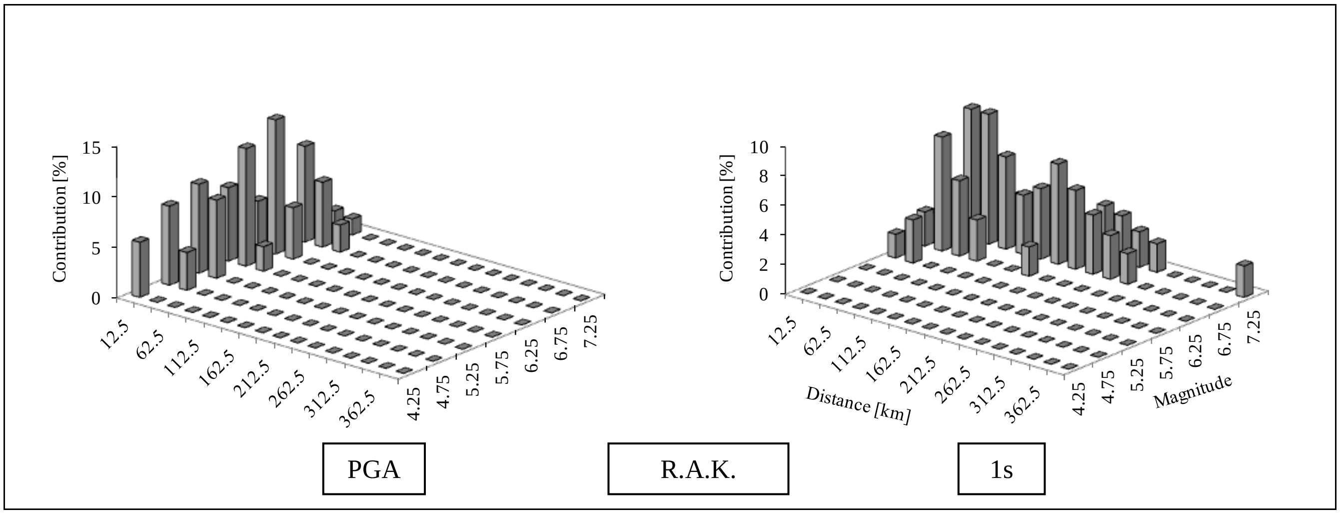


Fig. 3 – De-aggregation of hazard for R.A.K. (2475 years return period)

Figure 4 presents the Uniform Hazard Curves for major cities of UAE for a return period of 2475 years. This figure also signifies the difference between the hazard Fujaira and other Emirates. The spectral acceleration at

0.2s for Fujaira is almost twice that of R.A.K. The Uniform Hazard Spectra of Dubai, Sharjah, Ajman and Umm-Al-Quwain are very close to each other due to the fact that they spatially very close.

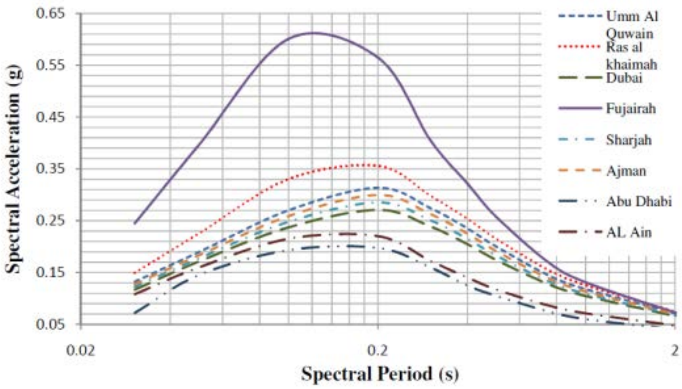


Fig. 4 – Uniform Hazard Spectrum for the eight cities of UAE

## 5. Site Response Spectra and Site Amplification Factors

### 5.1 Dynamic site response analysis

Different acceleration time histories were selected to perform the site response analysis using Shake 2000. An equivalent linear method is applied In SHAKE2000 to account for the nonlinearity of the soil deposit using an iterative procedure to obtain values for modulus and damping compatible with the equivalent uniform shear strain induced in each sub-layer [20]. The response spectra of the acceleration time histories were spectrally matched to the target response spectrum obtained from the seismic hazard analysis for the respective cities. The matching was performed by using RspmatchEDT software [54] which uses time domain algorithms to match the spectrum. Figure 5 shows typical result of spectral matching and comparison of the original and matched acceleration histories.

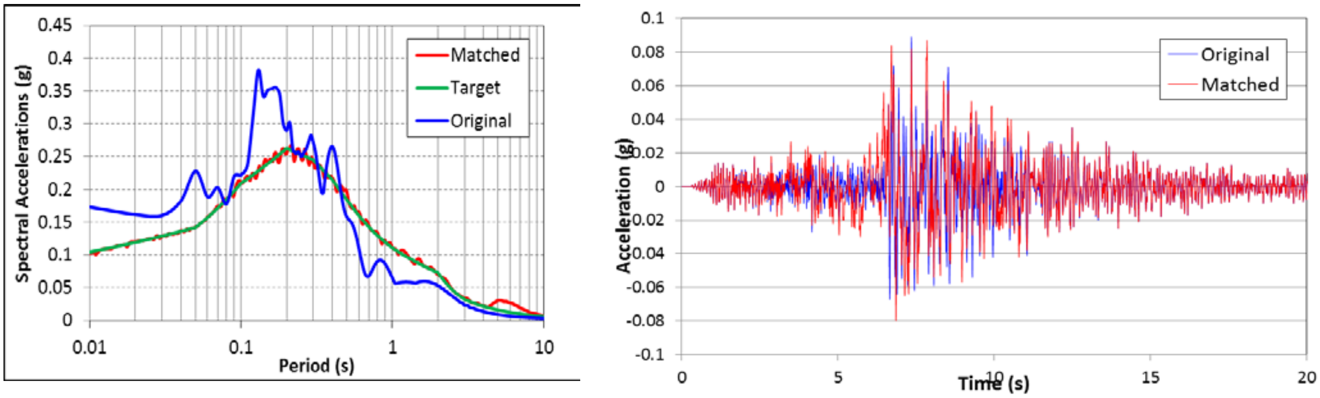


Fig. 5 – Typical spectral matching of response spectra.

### 5.2 Sites spectral response characteristics

Typical results of one-dimensional equivalent linear response analysis are presented in Figure 6. The analysis was performed on more than 100 site models for the major cities of UAE. The models were assigned site classes as per the provisions of IBC 2012 [55] based on the inferred shear wave velocity of the upper 30 m of soil column. The results presented in the following are for site classes C and D which represents the substantial majority of site class types in the area.

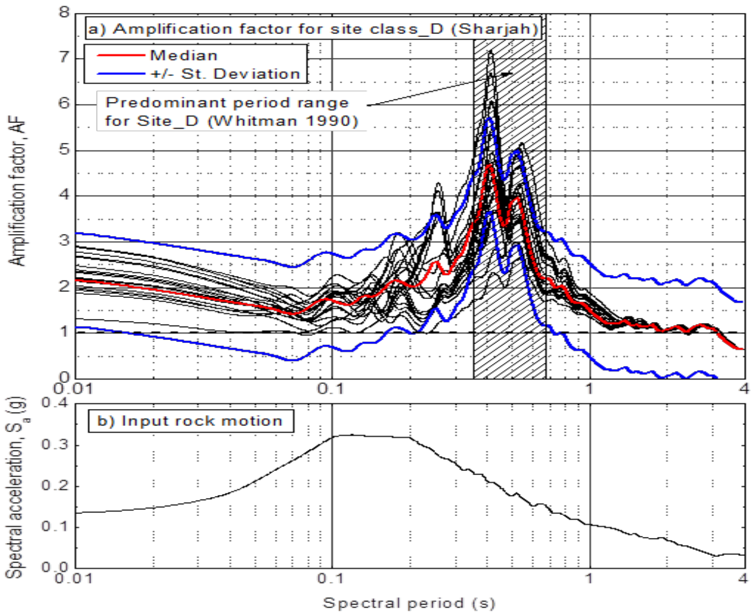


Fig. 6 – Typical results of site amplifications at different sites in the city of Sharjah

Figure 6 indicates that significant amplifications occur around 0.2s period which also corresponds to the predominant period calculated from the approach presented in [56].

The responses for a given site class were averaged for further analysis. The procedure of constructing design spectrum following IBC 2012 was used to best match the average response spectrum as shown in Figure 6. The amplification factors $F_a$ and $F_v$ were iterated until a best match was obtained. The factors obtained from this study are then compared with the factors given in IBC 2012 for respective site classes.

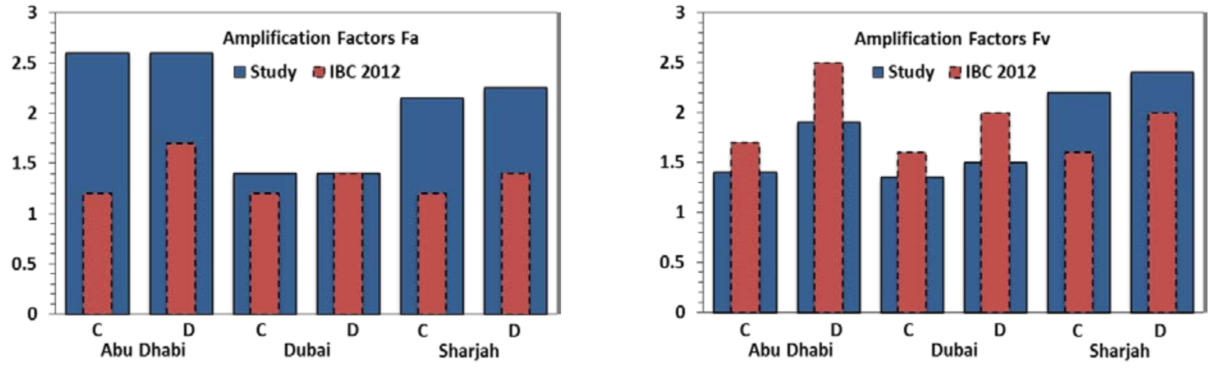


Fig. 7 – Comparison of amplification factors with IBC 2012 [46].

Figure 7 presents the amplification factors obtained from this study for site class C and D for the major cities of UAE. The amplification factors ($F_a$ and $F_v$) provided in the IBC 2012 are also presented for comparison purposes. The short period amplification factors ($F_a$) are higher than the factors in IBC 2012 for Sharjah and Abu Dhabi but remained similar to the code for Dubai (Site class D only). The long period amplification factors ($F_v$) are found to be smaller in this study than the factors specified in the code except for Sharjah. It is expected that the closer earthquakes will have significant effect on short structures (6 to 12 storeys) in the major cities of UAE. These structures represents the majority of structures being constructed in the major cities of UAE; therefore amplification factors specified in the building codes shall be factored higher for the construction of design spectra.

## 6. Conclusions

1. The study shows larger values of PGA and spectral accelerations compared to many published studies.
2. The seismic activity in Arabian Craton is significant for southern part of UAE. The contribution of Zagros region in Iran and Oman Mountains increases in the hazard towards the north of UAE.
3. Similarly the most likely scenario for southern of UAE is a strong earthquake occurring at long distance; however, strong earthquake at shorter period shall be considered as most likely scenario for northern regions of UAE.
4. The importance of local site effects on the amplification shall not be ignored as most of the amplifications occur at or around the theoretical natural period of the soil deposits.
5. Significant amplification occurs around periods of 0.1–0.5 s at most sites of Abu Dhabi, Dubai, and Sharjah. The shift in amplifications occur towards the longer periods for sites in Sharjah, whereas towards shorter periods for sites in Abu Dhabi and Dubai sites.
6. The amplifications factors specified by IBC (2012) for the construction of design response spectra are significantly smaller than found in this study for major cities of UAE.

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