Updating seismic hazard models for Kuwait

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Abstract

The valuable results from this research are the first and essential step for assessing seismic risk in Kuwait. The increase in the urban development and construction of tall buildings and skyscrapers in Kuwait necessitated an estimate of the seismic risk for creating a unified seismic code for Kuwait. This research comes to make the necessarily step by assessing the seismic hazard and deaggregation in the State of Kuwait. For this purpose, the historical and instrumental seismic catalogs of Kuwait and the active Zagros Seismic Belt were primarily compiled, unifying the magnitudes, removing unnecessary earthquakes (seismicity declustering) and considering the completeness of the catalogs. Multi-seismotectonic models for Kuwait region incorporate earthquake focal mechanisms, seismicity pattern, and structural geological situation have been created to reduce epistemic uncertainty. The recurrence parameters as well as the maximum expected earthquake from each seismic source were fundamentally estimated. Appropriate ground motion attenuation relation within a logic tree formulation was mainly used in creating hazard maps. A state-of-the-art probabilistic approach is used herein to produce hazard maps at return periods of 75, 475, 975 and 2475 years (equivalent to 50%, 10%, 5% and 2%, respectively, probability of exceedance in 50 years) at periods of PGA, 0.1, 1 and 4 seconds. The computations of hazard maps were constructed using spacing grid of 0.2° × 0.2° all over the Kuwait area. Uniform hazard spectrum and deaggregation charts have been adopted for all six governorates of Kuwait. These results with vulnerability index are the main components for estimating the seismic risk of Kuwait.

Introduction

Kuwait is located on the northeastern side of the Arabian Peninsula at the northwestern part of the Arabian Gulf, which borders it on the eastern side (Figure 1). It is bordered by Iraq to the north and the west, and Saudi Arabia to the south and west. It lies between latitudes 28° 27' 0" and 30° 3' 0" N and longitudes 46° 18' 0" and 48° 18' 0" E, and its area is 17818 km^2 (https://en.wikipedia.org/wiki/Kuwait). Kuwait is one of the most important oil producing and exporting countries in the world and has 10% of the world's oil reserves in its soil.

The seismic activity in the state of Kuwait is low to moderate (Abd el-aal et al 2020a 2020b and 2020c; Al-enzi et al 2007; Gu et al., 2017; Pasyanos et al., 2007). It was affected by several local earthquakes such as the January 16th, 1977 earthquake (local magnitude (Ml) = 4.5) which took place at 28.8° N and 48.1° E and the June 2th, 1993 earthquake (Ml = 4.8) which occurred at 29.0° N and 47.6° (Abd el-aal et al 2020a; Bou-Rabee and Nur 2002). After the earthquake that occurred in 1993, the Kuwaiti government decided to establish a national seismic network, and the establishment and operation of this network was assigned to the Kuwait Institute for Scientific Research (KISR). The network started recording earthquakes in 1997. The Kuwait National Seismic Network (KNSN) records local, regional and global earthquakes that occur in Kuwait and in the Globe. The KNSN has main center at Kuwait Institute of Scientific Research (KISR) and 8 field seismic stations distributed all over Kuwait (Abd el-aal et al 2020a; Gu et al 2018). This network has a very great impact in protecting modern urban development in the State of Kuwait. Earthquakes can cause many social and economic disasters if not well planned. Therefore, it is important to assess the seismic hazard in Kuwait for the purpose of mitigating seismic risk and developing seismic codes to design earthquake-resistant structures and protect strategic buildings.

In this study, the epistemic uncertainty treatment seismic hazard approach is used to assess the seismic hazard considering both local seismicity of Kuwait and regional seismicity from its surrounding regions. Many seismologists (e.g. Abd el-aal et al 2015; Bommer et al. 2004; Mostafa et al 2018; Rafi et al. 2013; Reiter 1990; Ur-Rehman et al. 2013; …etc) considered PSHA as the most valuable contribution to hazard assessment. PSHA was introduced by Cornell (1968) and modified by (McGurie 1978; Bender and Perkins 1987). It estimates the probability of exceeding or non-exceeding the ground motion at a certain level which is very important in assessing the chance of failure and designing building codes. The first step in the hazard analysis is to compile an earthquake catalog. It is followed by building a seismotectonic source model and estimating the recurrence parameters and maximum predicted magnitude in each seismic source specified in this model. Finally, a suitable ground motion attenuation relationship is applied to estimate the seismic hazard.

Seismic hazard maps were constructed using a grid of 0.2° all over the Kuwait area to produce 5 % damped spectral acceleration values on bedrock for the peak ground acceleration (PGA) and spectral periods of 0.1, 1 and 4 seconds at return periods of 75, 475, 975 and 2475 years (equivalent to 50%, 90%, 95% and 98%, respectively, probability of non-exceedance of ground motion in 50 years). Uniform hazard spectrum (UHS) was estimated at Kuwait city, Hawally, Mubarak Al-Kabeer, Sabah Al Ahmad, Al Farwaniyah and Al Jahra to determine the hazard at spectral periods ranging from 0 to 4 seconds. These periods are the most important for the earthquake engineering designer. Also, deaggregation charts were adopted in the same cities to determine the scenario events that mostly contribute to the hazard level for spectral periods of 0.1 and 2 seconds at return period of 475 years. The 475 years is the primary return period for most building codes.

Regional seismicity and seismotectonic

The State of Kuwait, being relatively located in the northeastern part of the Arabian Peninsula, was fundamentally affected by the collision of Zagros fold belt in Iran (Figure 2a). A number of scientists have studied the structural and tectonic situation of the region (Abd el-aal et al 2020a 2020b and 2020c; Al-enzi et al 2007; Carman, 1996; Pasyanos et al., 2007; Laske et al. 2013). The rate of crustal shortening along the Zagros Thrust fold belt is about 10 mm/year in the southeast and decreases to be 5 mm/year in the northwest (Allen et al. 2004; Vernant et al. 2004). Small, medium and large earthquakes with magnitudes reach to 7.5 took place along this belt at shallow, medium and deep depths (Figure 1). This high seismicity active Pliocene belt is 1500 km long and 200 to 300 km wide. It extends from eastern Turkey in the north to Oman in the south in NW-SE direction (Jackson and McKenzie 1984; Berberian 1995; Hessami et al. 2003). Due to the movement and uplift of mountains primarily caused by the convergence zone and erosion in the region, a sedimentary cover from 7 to 10 km thick was mainly formed.

Reilinger et al. (2006) has studied the focal mechanisms of some earthquakes along the Zagros belt and inferred thrust faults with dip angle of 40°-50° (Figure 2b). Carman (1996) indicated that the maximum principal horizontal stress field is trending in a NE-SW direction (Kuwait Arch). The surface topography of Kuwait is mostly mapped by the steep folding of the Zagros belt in a NW-SE direction. The anticlines, which formed during the Cretaceous period, in the Quaternary deposits of the large Burgan Oil Field in southern Kuwait showed clear evidence of continued movement and uplift in the region.

Local seismicity and structure setting

The State of Kuwait has relatively low to moderate seismic activity (Abd el-aal et al 2020a 2020b and 2020c; Gu et al., 2017; Pasyanos et al., 2007). No historical earthquakes have been accurately documented prior to 1900. In the twentieth century, earthquakes were instrumentally recorded inside Kuwait such as July 5, 1931, March 14, 1973, January 2, 1976, September 26, 1976, September 27, 1976, January 16, 1977, and July 1, 1993 earthquakes with magnitudes 4.7, 4.6, 4.1, 3.2, 3.8, 4.5, and 4.8, respectively. The 1993 Kuwait earthquake caused some damages and property in Kuwait City (Abd el-aal et al 2020a; Gu et al., 2017; Pasyanos et al., 2007). Figure (1) shows the seismicity of Kuwait, Zagros belt and their surroundings.

After the establishment of the KNSN, seismologists become able to record very small earthquakes occurring in Kuwait. Hence, they can determine the seismic sources with high accuracy. Two seismic sources were identified, namely, Minagish_Umm Gudair and Raudhatain-Sabriya sources in southwestern and northeastern Kuwait, respectively. Abd el-aal et al (2020a) and Pasyanos et al. (2007) believe that earthquakes are caused by oil extraction, particularly those that occurred near the oil fields. Figure (2c) shows that Kuwait structures consist of structural arches, anticlines, synclines, regional gradients, troughs, stylolites, fractures and faults (Carman, 1996). Al-enzi et al (2007) studied the focal mechanism of 33 earthquakes in Kuwait using the composite 1st motion polarity of P-waves. It shows that the state of Kuwait is affected by strike slip faulting with normal and reverse components (Figure 2d).

Methodology

The probabilistic seismic hazard approach (PSHA) is used to assess the seismic hazard in the state of Kuwait based on Cornell (1968) procedure. Later, this procedure was amended by McGuire (1978) and Bender and Perkins (1987). The probability for the ground motion level to be exceeded within a particular period of time is obtained from the following equation:

$$P_t(z) = \sum_{j=1}^{k} \int_{m=M_{min}}^{m=M_{max}} P_t(m) \int_{r=R_0}^{R_{max}} P(r) \ (P(A \geq Z)m, r) \ dmdr \quad (1)$$

where $P_t(m)$ is the probability of an earthquake occurrence of magnitude m in the seismic source j over t years, $P(r)$ is the probability of an earthquake occurrence in a seismic source at a distance r from a given site and $P(A \geq Z)$ is the probability that the ground motion A will exceed the ground motion level Z at a specific site.

The first step in the hazard analysis after compiling the earthquake catalog is to build up a seismotectonic source model to define the seismicity of each source based on all the available information about the geology, structure, tectonic and seismicity in the study area. Next, the seismicity recurrence parameters are estimated to determine the probability of occurrence of an earthquake of a certain magnitude within each seismic source during a particular time period. In addition, the maximum earthquake magnitude (M_{max}) is estimated for all the seismic sources to evaluate the seismic risk at a given site where critical structures are planned. M_{max} indicates the amount of rock displacement that is likely to occur along the fault plane. In other words, whenever a strong earthquake takes place, the amount of rocks displacement is increased and vice versa. Finally, a ground motion relation is used to attenuate earthquakes generated in each seismic source in relation to earthquake magnitude and distance to the site. In this study, the Poisson model was used to estimate the earthquake magnitude exceedance rate for each seismic source. Also, the epistemic uncertainties were reduced by using alternative seismotectonic source models and ground motion relationships within a logic tree formulation. Figure 3 illustrates the procedure chart used in this study.

Inputs for PSHA

1. Catalog Data

The first important step in any seismic hazard assessment is building a complete, uniform and reliable earthquake catalog containing all the available instrumental besides the historical earthquakes from many different sources. In this study, instrumental earthquakes from 1907 to 2019 were gathered from different sources. The local events in Kuwait from 1997 to 2019 were obtained from the KNSN (http://www.kisr.edu.kw).

The earthquakes data recorded by the Kuwait National Seismic Network (KNSN) was on the local magnitude scale (Ml) and was converted to the moment magnitude scale using a linear regression relation which was developed for this purpose. The limited available moment earthquake data in Kuwait were used to establish the relationship between the local magnitude scale and the moment magnitude scale in Kuwait (Figure 4) with 95% confidence bounds as follows:

$$Mw = 0.87(Ml)\ (\pm 0.07) + 0.2392\ (\pm 0.2) \quad (2)$$

Where (Mw) is the moment magnitude. Ml refers to local magnitude used in KNSN.

Regional and Teleseismic events from 2008 to 2019 were gathered from the European Mediterranean Seismological Center (EMSC) (http://www.emsc-csem.org). In addition, Regional events from 1907 to

2010 as well as the historical seismic events from 628 to 1898 were gathered from the catalog of Deif et al. (2017).

All these data were gathered in one catalog after excluding all the duplicated events. All the events were unified to the Mw scale. The Mw is the most reliable magnitude scale that takes into account the rupture are on the fault surface, the amount of displacement along the fault plane during an earthquake and the strength of the rock. The catalog declustering was applied using Gardner and Knopoff (1974) windowing technique to remove the dependent earthquakes (foreshocks and aftershocks). This technique makes the catalog look like a Poisson dataset (Van Stiphout et al. 2012). Figure (1) shows the historical and instrumental seismicity of Kuwait and its surroundings from 628 to 1898 and from 1907 to 2019, respectively. Only the medium and large earthquakes that took place outside Kuwait with a magnitude of ≥ 4 were used in the hazard analysis, but only in the state of Kuwait the small earthquakes with Mw ≥ 2.5 were also used. The total number of earthquakes in the resultant catalog is 4957 events.

2. Seismotectonic models

The seismotectonic model defines the geographical boundaries of the seismic sources capable of generating earthquakes. Each of these seismic sources has a unique stress regime and seismicity level and each point within it is assumed to have the same probability of being the epicenter of a future earthquake. These seismic sources could be area, line (fault), point, volume sources or dipping planes (Lee and Trifunace 1985). The seismotectonic models are absolutely essential in both seismic hazard studies and earthquake forecasting.

In this study, the boundaries of the seismic sources in the seismotectonic model were made up of area sources and defined on the basis of the geographical distribution of earthquakes' epicenters, structure and tectonic settings, seismic activity and previous focal mechanism studies. Two alternative seismotectonic models were constructed to account for the epistemic uncertainties (Figure 5). The first seismotectonic source model is composed of 27 seismic sources to describe in detail the seismicity of the study area. However, the second model is composed of 12 sources and describes the regional seismicity of the area. In addition, a background seismic source has been defined in both seismotectonic models to describe the floating earthquakes outside the defined seismic sources. Both of these models were combined within a logic tree formulation to further take the epistemic uncertainties into account. Estimates of this logic tree formulation are referred to as the third seismotectonic source model in the next sections just to describe the results in an easier and more comfortable manner.

3. Recurrence parameters and M_{max}

To accurately estimate the earthquake recurrence parameters and predict the maximum earthquake magnitude in each seismic source for the seismotectonic models, the seismicity of each source should be modeled first by estimating the so-called the magnitude of completeness (*Mc*). The *Mc* is the minimum magnitude at which all earthquakes in an area have been identified over a specified period of time (Kijko and Graham 1999; Rydelek and Sacks 2003; Wiemer and Wyss 2000). The earthquakes in each seismic source were used to build sub-catalogs where each one was subdivided to 1-unit magnitude bin. Then, the cumulative number of events in each bin was plotted versus time starting from the time of the recent earthquake (Figure 6). The time at which the slope of the cumulative plot begins to change is the level of completeness.

Now, the seismicity recurrence parameters can be estimated to indicate the probability of earthquake occurrence with time at any point in the seismic source. The recurrence parameters include β, b-value and λ and are estimated herein using the maximum likelihood method of Weichert (1980). The parameter β is very significant in defining the tectonics of each seismic source. It can be estimated from the relationship (β = b ln10) where b is the b-value of the Gutenberg and Richter (1956) relationship. The b-value is the relative ratio of small and large magnitude earthquakes. The variations in b-values indicate the variation in stress regimes. Low b-value indicates high stress in a specific region and vice versa. The parameter λ is the activity rate and is defined as the number of earthquakes that occur annually.

Moreover, the maximum earthquake M_{max} that can be generated in the seismic source is estimated in some sources using the Robson-Whitlock-Cooke method (Robson and Whitlock 1964; Cooke 1979; Kijko and Singh 2011). In other sources that have incomplete data, the procedure provided by Kijko (2004) is used to estimate M_{max}. Finally, the predicted M_{max} was estimated by adding 0.5 magnitude unit to the maximum observed magnitude (M_{max} obs.) in the seismic sources with very few events. The seismicity recurrence parameters and M_{max} with their corresponding standard deviations (STD) for the first and the second seismotectonic source models are listed in Tables (1) and (2), respectively.

4. **Ground motion attenuation relations**

The attenuation models define the probabilistic relation between earthquake magnitudes, source to site distance and acceleration. It should be carefully chosen to attenuate earthquakes generated in each seismic source. The lack of ground motion records in Kuwait makes it necessary to use already developed attenuation relations to predict the ground motion from the earthquakes' epicenter to a specific site. Two alternative attenuation relations were used in the current study: the first one is the García et al. (2005) that was used to model the ground motion in the seismic sources located in the state of Kuwait and the second is the Abrahamson and Silva (1997) which was applied to model the ground motion in the sources surrounding Kuwait for the three seismotectonic source models. Also, these attenuation relations use the Mw scale to predict the ground motion on the rock sites for PGA and spectral accelerations for different periods.

Uncertainty treatment

In this study, the uncertainty was reduced using alternative seismotectonic source models within a logic tree framework (Figure 3). As is known, the statistical variability in the definition of the seismic sources in the seismotectonic model and in the attenuation relationships are the main sources of epistemic uncertainty. Alternatives ground motion equation relations were also used to diminish the effect uncertainty in the hazard calculations. In addition, the maximum predicted earthquake magnitude was estimated using three different methods depending on the completeness of the sub-catalogs, the number of events in each seismic source and the quality of the data to ensure reliable and precise estimates of the M_{max} which is a very important parameter in the probabilistic seismic hazard assessment.

Results And Discussion

1. **Seismic hazards maps**

Seismic hazard was estimated using CRISIS (2015) software at 324 sites distributed over a 0.2° x 0.2° spaced grid in Kuwait and surroundings to avoid extrapolation of the results. Hazard maps were created to produce 5 % damped spectral acceleration values for PGA and spectral periods of 0.1, 1 and 4 seconds on bedrock for the three seismotectonic source models. Figures (7 to 18) show the computed seismic hazards for return periods of 75, 475, 975 and 2475 years, which are equivalent to 50%, 10%, 5% and 2%, respectively, probability of exceeding the ground motion in 50 years which is the expected design life for a building. These return periods, especially the 475 years, are very important in most seismic building codes.

The hazard maps show that the level of the seismic hazard in Kuwait is low to moderate. It is increasing at the Sabriya and Minagish oil fields in the northeast and southwest of Kuwait, respectively, especially at the PGA and the short spectral period of 0.1 second, indicating that the origin of seismicity in this area is of induced type. The level of seismic activity at Minagish oil field is higher than at the Sabriya oil field. The seismic hazard results for the first, second and third seismotectonic source models showed that the highest PGA values are 49.1, 52.36 and 64.62 gals, respectively, at return period of 475 years in the south of Kuwait. To the northeast of Kuwait state, the hazard level increases due to the collision of Zagros fold belt in Iran. These results highly reflect the seismotectonic setting of the area.

All the seismic hazard maps show the highest acceleration values at the short spectral period 0.1 second while the lowest acceleration values appear at the long spectral period 4 second. All maps with the same spectral accelerations at different return periods for the three source models have the same contour line pattern. It is clearly observed that the hazard pattern is affected by the geometry of the seismotectonic source models especially at the PGA and 0.1 seconds spectral period. The background seismic source has a negligible effect on the hazard calculations because it represents areas of low seismicity. The hazard maps show higher acceleration values at the 2475 years return period, and by increasing the probability of exceeding ground motion in 50 years, the acceleration values become lower.

In general, the hazard results for the three seismotectonic models are close to each other, with the detailed first model showing the lowest acceleration values and the third model having the highest values at PGA and 0.1 second spectral period. However, the second model shows the lowest acceleration values at the long spectral periods of 1 and 4 seconds. In addition, the results of this study were compared with the results of previous studies (i.e. Al-shijbi et al. 2018, Sadek 2004, ….etc) and showed a good agreement in the regional seismicity pattern of Kuwait and provided an accurate and detailed estimate of the seismic hazard in the state of Kuwait over a 0.2° grid taking into account the teleseismic, regional and local seismicity. The results also reflect the tectonics and seismic activity of the area confirming the accuracy and reliability of the estimates. These maps can be used by the earthquake engineer for earthquake-resistant design, national and strategic projects, building codes and seismic risk mitigation.

2. UHS

Uniform hazard spectrum (UHS) was estimated at all six governorates of Kuwait state, namely: Kuwait city, Hawally, Mubarak Al-Kabeer, Sabah Al Ahmad, Al Farwaniyah and Al Jahra (Figure 1). UHS is used to determine the seismic hazard at spectral periods ranging from 0 to 4 seconds at return periods of 75, 475, 975 and 2475 years on bedrock for the three seismotectonic models (Figures 19, 20 and 21). The results show the highest acceleration values at spectral period of 0.1 second for all return periods for the three seismotectonic models except for Kuwait city, which shows the highest acceleration at spectral period of 0.2 second for all return periods for only the second model. Also, the highest acceleration at Mubarak Al-Kabeer is shown at spectral period of 0.2 second for the 75, 475 and 975 years return periods. In addition, the highest acceleration in Hawally is shown at spectral period of 0.1 second except for the first and second models at 75 and 475 years return periods, respectively, where the highest accelerations are 43.87 and 82.68 gals, respectively, at spectral period of 0.2 second.

Al Jahra exhibits the highest level of seismic activity among the six governorates of Kuwait for the three seismotectonic models. The seismic hazard at Al Jahra for spectral period of 0.1 second at 475 years return period is 122, 95 and 130 gals for the first, second and third models, respectively. The acceleration values increase with decreasing the probability of exceeding ground motion in 50 years. As shown from the figures, the hazard is highest at 2474 years return period and lowest at 75 years return period. The first model shows the lowest acceleration values at the short periods spectral acceleration values. However, the second model gives the lowest accelerations at long periods spectral acceleration values. The third model shows the highest acceleration values at all spectral accelerations.

The first and third models show the same seismicity level for the six governorates. The order of seismic hazards in these governorates from highest to lowest is: Al Jahra, Sabah Al Ahmad, Al Farwaniyah, Kuwait city, Hawally and Mubarak Al-Kabeer. On the other hand, the arrangement of seismic hazards in these governorates from the second seismotectonic model from highest to lowest is: Sabah Al Ahmad, Al Farwaniyah, Al Jahra, Mubarak Al-Kabeer, Hawally and Kuwait city. The slight difference between the results from these alternative models reduces the uncertainties in the hazard calculation. These results are very useful in earthquake engineering designs.

3. Deaggregation

Deaggregation of seismic hazards was estimated to specify the contribution of both earthquake magnitude and source to site distance to the hazard at all six governorates of Kuwait for spectral periods of 0.1 and 2 seconds at return period of 475 years for the three constructed seismotectonic models. These deaggregation charts are very useful in determining the dominant hazardous event at a specific site to be used by the earthquake engineer. The deaggregation of seismic hazards at the six governorates of Kuwait for the short spectral period of 0.1 second for return period of 475 years for the first, second and third seismotectonic source models are shown in Figures (22, 23 and 24, respectively). Figure (22) shows that most of the hazard comes from moderate earthquakes with Mw ranging from 4 to 5 located at very short distance from these governorates. Figures (23 and 24) show that most of the hazard comes from moderate earthquakes with Mw ranging from 4 to 5) located at very short distance from the sites. Besides, Kuwait city and Hawally show a smaller contribution to the hazard from nearby large earthquakes (Mw > 6) for the second and the third models. These nearby medium size earthquakes will pose a small risk due to their short duration (0.1 second) and low energy content.

Figures (25, 26 and 27) show the deaggregation of seismic hazards at the six governorates for the long spectral period of 2 second for return period of 475 years for the first, second and third seismotectonic source models, respectively. Figure (25) shows that the most severe impact on the sites come from nearby large earthquakes (Mw > 6). Also, a smaller contribution to the hazard comes from large events that are very far away. Figure (26) shows that the most contribution of hazard on the sites come from nearby large earthquakes (Mw > 6) and only Al Jahra shows that there is an additional lower hazard from large earthquakes located at large distances > 800 km. The results of the third model (Figure 27) show that the hazard is dominated by nearby large size earthquakes (Mw > 6) and only Al Jahra and Sabah Al Ahmed show that there is an additional lower hazard from large earthquakes that are very far away. These nearby large earthquakes will pose a high risk due to their long duration (2 second) and high energy content. The deaggregation results from the three models show that the governorates of Kuwait are affected by nearby moderate to large earthquakes which can produce high values of ground acceleration, which would pose a high risk if not well planned.

Summary and conclusions

In this study, the seismic hazard of the state of Kuwait was assessed using the epistemic uncertainty seismic technique as a first and important step before assessing seismic risk in the study area. An earthquake catalog was compiled from many different sources for use in the PSHA and for demonstrating the seismicity of Kuwait and the Zagros Thrust fold belt from the period 1907 to 2019. The catalog was unified, removed the foreshocks and aftershocks and estimated the magnitude of completeness to ensure its quality and homogeneity. Earthquakes with a moment magnitude ≥ 4 were considered in the seismic hazard analysis. In addition, local events with a moment magnitude ≥ 2.5 that occurred in Kuwait during the period from 1997 to 2019 were used as the catalog was complete during this time span due to the establishment of the KNSN stations.

Alternative seismotectonic models were built based on all the available geological, structural, tectonic, geophysical, seismotectonic and seismological data of Kuwait, Iraq, Iran, Saudi Arabia and the United

Arab Emirates to consider the effects of local and regional seismic sources. The recurrence parameters β, b-value and λ with their corresponding slandered deviations were estimated for each seismic source using the maximum likelihood method. The maximum earthquake for each source was predicated as it very important input parameter in the hazard calculation. It indicates the amount of rock displacement that is likely to occur during an earthquake. The epistemic uncertainties were reduced by using alternative seismotectonic models and attenuation relations within a logic tree formulation.

Maps were created to show the seismic hazard for periods of PGA, 0.1, 1 and 4 seconds for return periods of 75, 475, 975 and 2475 years (corresponding to probabilities of 50%, 10%, 5% and 2%, respectively, for ground motion exceedance in 50 years). These maps show that Kuwait is affected by low to moderate seismic activity. The highest seismic level is at the Minagish oil field area in the southwest. Another activity is has been found at Sabriya oil field in the northeast, indicating that these areas are affected by induced seismicity. Higher values of acceleration are observed at the short spectral periods as well as at the long return periods.

UHS were estimated at six governorates to show the hazard at a set of spectral periods ranging from 0 to 4 seconds, which are the most important to the seismic engineer for return periods of 75, 475, 975 and 2475 years on bedrock. The highest acceleration is observed at spectral period of 0.1 second except for some localities which showed the highest value at 0.2 second for some return periods in the seismotectonic models. The results of the three models showed the highest hazard in the state of Kuwait at Sabah Al Ahmad which is located in the south of Kuwait at the eastern boundary of the Arabian plate.

Moreover, the seismic hazard was disaggregated as a function of magnitude and distance to indicate the scenario events that contribute more to the seismic hazard at each of the six governorates of Kuwait for spectral periods of 0.1 and 2 seconds at return period of 475 years for the three seismotectonic models. In general, the results showed that the most severe impact on the six sites is dominated by nearby medium size earthquakes at the short spectral period of 0.1 second, which means that small risks can be expected due to the short duration and low energy content. However, they are dominated by nearby large size earthquakes at the long spectral period of 2 second, which means that high risks can be expected due to the long duration and high energy content. The results of this study are consistent with the seismicity and tectonic setting of the study area. The reliable estimates of acceleration at variable spectral accelerations and different return periods provide guidance for an earthquake engineer to build safe structures that can resist ground motion in the event of an earthquake. These results can be very helpful to create a unified seismic code for Kuwait.

Declarations

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Tables

Table 1: Seismicity recurrence parameters and M_{max} for the first seismotectonic source model.

Seismic source	M_{min}	M_{max} obs.	M_{max}	STD	β	STD	b	STD	λ	STD
1	2.5	4.8	5.3	0.77	2.08	0.19	0.9	0.08	2.39	0.401
2	2.5	4.5	5	0.91	2.09	0.26	0.91	0.11	1.637	0.319
3	2.5	4.2	4.7	0	2.29	0.42	0.99	0.18	0.901	0.34
4	4	6.5	7.1	0.65	1.6	0.2	0.7	0.09	0.941	0.193
5	4	6.3	6.5	0.34	1.5	0.19	0.65	0.08	0.957	0.169
6	4	7.3	7.5	0.3	1.75	0.08	0.76	0.04	0.707	0.043
7	4	6.4	6.7	0.64	1.83	0.25	0.8	0.11	0.377	0.07
8	4	5.9	6.1	0.31	1.65	0.21	0.72	0.09	1	0.201
9	4	6.7	6.9	0.32	1.32	0.12	0.57	0.05	1.18	0.17
10	4	6.4	6.5	0.27	1.73	0.1	0.75	0.05	1.754	0.185
11	4	5.1	5.3	0.34	2.16	0.41	0.94	0.18	0.388	0.132
12	4	6.7	6.8	0.26	1.7	0.07	0.74	0.03	0.901	0.047
13	4	6.9	7	0.26	1.59	0.05	0.69	0.02	1.395	0.069
14	4	5.9	6.1	0.33	1.62	0.25	0.7	0.11	0.723	0.144
15	4	5.8	6.1	0.4	1.93	0.25	0.84	0.11	1.51	0.324
16	4	5.8	6.1	0.36	2.05	0.28	0.89	0.12	1.183	0.298
17	4	6.1	6.2	0.27	1.54	0.27	0.67	0.12	0.8	0.161
18	4	6.4	6.5	0.26	1.19	0.2	0.52	0.09	0.242	0.037
19	4	6.5	6.7	0.31	1.64	0.14	0.71	0.06	0.884	0.113
20	4	6.5	6.7	0.33	1.53	0.19	0.67	0.08	0.417	0.063
21	4	6.8	7.3	0.91	1.79	0.22	0.78	0.09	1.389	0.382
22	4	4.4	4.6	0.31	2	0.45	0.87	0.19	0.217	0.088
23	4	7.1	7.6	0.61	0.91	0	0.39	0	0.025	0.006
24	4	7.1	7.6	0	1.36	0.29	0.59	0.13	1.901	0.645
25	4	4.7	4.9	0.3	2.24	0.44	0.97	0.19	1.626	0.607
26	4	5	5.2	0.3	1.87	0.33	0.81	0.14	3.803	0.864
27	4	7	7.1	0.47	1.4	0.22	0.61	0.1	0.08	0.013

BG	4	5.1	5.2	0.33	1.93	0.4	0.84	0.18	0.26	0.067

Table 2: Seismicity recurrence parameters and M_{max} for the second seismotectonic source model.

Seismic source	M_{min}	M_{max} obs.	M_{max}	STD	β	STD	b	STD	λ	STD
1	2.5	4.8	5.3	0.63	2.11	0.19	0.91	0.08	2.919	0.542
2	2.5	4.5	5	0.81	2.09	0.25	0.91	0.11	1.734	0.329
3	4	6.5	7.1	0.62	1.59	0.2	0.69	0.09	0.953	0.195
4	4	6.3	6.5	0.3	1.56	0.18	0.68	0.08	0.162	0.017
5	4	7.3	7.5	0.29	1.75	0.08	0.76	0.03	0.866	0.055
6	4	6.7	6.8	0.26	1.68	0.08	0.73	0.03	1.654	0.142
7	4	6.7	6.8	0.26	1.69	0.06	0.74	0.03	0.994	0.054
8	4	6.9	7	0.26	1.57	0.05	0.68	0.02	2.192	0.138
9	4	6.5	6.8	0.3	1.58	0.16	0.69	0.07	0.579	0.081
10	3.8	7.1	7.6	0.91	1.39	0.15	0.6	0.07	3.929	0.839
11	3.95	6.8	7.3	0.88	1.8	0.21	0.78	0.09	1.848	0.504
12	4	7	7.1	0.49	1.21	0.24	0.53	0.1	0.054	0.011
BG	4	5.1	5.2	0.33	1.74	0.41	0.76	0.18	0.23	0.062