Article

Probabilistic Seismic Hazard Assessment for United Arab Emirates, Qatar and Bahrain

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Received: 24 September 2020; Accepted: 5 November 2020; Published: 7 November 2020

Abstract: A probabilistic seismic hazard assessment in terms of peak ground acceleration (PGA) and spectral acceleration (SA) values, for both 10% and 5% probability of exceedance in 50 years, has been performed for the United Arab Emirates, Qatar, and Bahrain. To do that, an updated, unified, and Poissonian earthquake catalog (since 685 to 2019) was prepared for this work. Three alternative seismic source models were considered in a designed logic-tree framework. The discrimination between the shallow and intermediate depth seismicity along the Zagros and the Makran regions was also considered in this assessment. Three alternative ground-motion attenuation models for crustal earthquakes and one additional for intermediate-depth ones have been selected and applied in this study, considering the predominant stress regime computed previously for each defined source. This assessment highlights that the maximum obtained hazard values are observed in the northeastern part of the studied region, specifically at Ras Al-Khaimah, Umm Al-Quwain, and Fujaira, being characterized by mean PGA and SA (0.2 s) pair values equal to (0.13 g, 0.30 g), (0.12 g, 0.29 g), and (0.13 g, 0.28 g), respectively, for a 475-year return period and for B/C National Earthquake Hazards Reduction Program (NEHRP) boundary site conditions. Seismic hazard deaggregation in terms of magnitude and distance was also computed for a return period of 475 years, for ten emirates and cities, and for four different spectral periods.

Keywords: seismic hazard; peak ground acceleration; deaggregation; uniform hazard spectra; zagros-biltis fold thrust belt; makran subduction zone; United Arab Emirates; Qatar; Bahrain

1. Introduction

During the last few decades, the Arabian (Persian) Gulf countries (United Arab Emirates (UAE), Qatar and Bahrain) have experienced huge economic growth reflected by the development of their infrastructure and construction industry, as well as a considerable increase of population. Several significant national projects worth billions of dollars have been built, or are under construction, in those countries (e.g., Khalifa Tower, Dubai Metro, Dubai Creek Tower, Expo 2020 Dubai in the UAE; FIFA World Cup Qatar 2022 stadiums, Sharq Crossing, Lusail City, Water Security Mega Reservoir Project, and Hamad Airport expansion project in Qatar; Bahrain World Trade Centre, Abraj Al Lulu, Bahrain Financial Harbour, and Durra Al Bahrain in Bahrain).

Geographically, the three countries (Figure 1) share the political sea borders of the Arabian Gulf with Iran. Tectonically, they are located within the eastern part of the stable continental region of the
“Arabian Plate”, which was formed 25–30 million years ago due to the opening of the axes of the Great African Rift System [1] along the Red Sea and the Gulf of Aden. Significant potential seismotectonic sources are surrounding those regions [2]: (a) the Zagros-Biltis Fold Thrust Belt (ZBFTB) from the northeastern side [3], (b) the Makran Subduction zone defining the Arabian-Eurasian plate boundary, towards the east [4], and (c) the Owen-Murray Transform plate boundary delimiting the Arabian and Indian Plates, towards the southeastern border [5] (Figure 1a). Significant earthquake activity was recorded along the previously mentioned plate boundaries (Figure 1b). Despite the large distance between those plate boundaries and the studied countries, they are the main potential contributors to the seismic hazard in these countries.

Figure 1. Regional tectonic setting (a), and shallow and intermediate-depth Poissonian earthquakes (since 658 to 2019) for the surroundings of UAE, Qatar and Bahrain (b) [2,6]. Earthquake sizes have been drawn relative to the moment magnitude.

The current building regulations [7–9] of the studied countries (UAE, Qatar, and Bahrain) are not fully compatible with the seismic design concepts of the modern building codes around the world. The best and most effective way to mitigate such natural phenomena and reduce disasters caused by earthquakes is to compute reliable seismic hazard values that greatly serve to improve what is
considered in building regulations. The computation of these probabilistic seismic hazard values establishes the crucial first step towards reaching a reliable and representative seismic provision in the building codes for any region or country. Taking into consideration the substantial development and mega construction projects in those countries, as well as the current incomplete and non-uniform regulations for the seismic design, a new comprehensive seismic hazard assessment based on a systematic approach is required.

In the current work, a new probabilistic seismic hazard assessment (PSHA) for the three Gulf countries is developed in terms of the mean horizontal peak ground acceleration (PGA), hazard curves, and spectral acceleration (SA) ordinates. A typical zoning approach combined with a spatially smoothed seismicity model has been applied based on an up-to-date compiled and unified Poissonian earthquake catalog and a seismic source model published recently by Sawires et al. [2,6]. A logic-tree design that considers the epistemic uncertainties related to four main inputs has been constructed: the seismic source model, the Gutenberg–Richter \( b \)-value, the maximum expected magnitude, and the ground-motion attenuation model. Here, we present the results of this detailed seismic hazard assessment for the whole studied region, in general, and for selected mega cities in particular, for B/C National Earthquake Hazards Reduction Program (NEHRP) boundary site conditions, and for return periods of 475 and 975 years. This study, initially, will provide engineers and designers with the necessary updated seismic hazard values (PGA and SA), hazard curves, and uniform hazard spectra (UHS), in order to update and/or create a uniform building code for those countries. A significant result from this assessment has been the deaggregation analysis, providing the necessary data of the most contributing seismic sources to the hazard at a particular site, which could be used by engineers and analysts to both select the ground-motion acceleration records and generate scenario earthquakes required for the seismic design. This assessment also provides the necessary seismic zoning maps, as well as a new proposed design spectrum, that are fully compatible with the requirement of the new building codes all over the world.

2. Review of Previous Assessments and Building Regulations

Since 1990s, several seismic hazard assessments have been conducted in the Arabian Gulf region including the countries of UAE, Qatar, Bahrain, Oman, and Saudi Arabia. Depending on their availability, they are arranged chronologically as the following: Al-Haddad et al. [10], Grünthal et al. [11], Abdalla and Al-Homoud [12], Sigbjørnsson and Elshai [13], Peiris et al. [14], Musson et al. [15], Malkawi et al. [16], Aldama-Bustos et al. [17], Shama [18], El-Hussain et al. [19], Khan et al. [20], and Al-Shijbi et al. [21]. Table 1 represents an attempt to shed light on and compare those seismic hazard assessments performed previously upon the surroundings of the region of interest. Terms of comparison are the study region (local, regional, or specific sites), the applied attenuation relationships based on the considered seismic sources, the software code used, and the main output results. As it can be seen from Table 1, some of these studies were conducted in order to assess the seismic hazard at a regional level, like those for the Middle East [11], the Arabian Peninsula [10,21], or the Arabian Gulf countries [14,19]. While, other studies focused on the UAE (e.g., [12,15,20]), or specifically on some important big cities (e.g., [13,16–18]).
Table 1. Description of previously published regional and local PSHAs performed upon the study area.

| The Study                        | Study Region                        | Attenuation Relationships                                                                 | Software Code              | Results                                                                                     |
|----------------------------------|-------------------------------------|-------------------------------------------------------------------------------------------|----------------------------|---------------------------------------------------------------------------------------------|
| Abdalla and Al-Homoud [12]       | The UAE and its surroundings        | Zare [36] model that was derived for the Zagros region.                                    | EQRISK [37]                | PGA map for a return period of 475 years                                                     |
| Sigbjornsson and Elnashai [13]   | Dubai, UAE                          | Models by Ambraeys et al. [22] and Simpson [38] were applied to all defined seismic sources.| Not provided              | Hazard curves, UHS, and PGA values for return periods of 475, 975 and 2475 years.            |
| Peiris et al. [14]               | The Arabian Gulf including Dubai and Abu Dhabi | Models by Dahle et al. [39] and Atkinson and Boore [33] were applied for the Arabian stable craton, while those by Ambraeys et al. [22] and Sadigh et al. [40] were considered for the Zagros and Makran regions. | Not provided              | Hazard curves for the selected cities, UHS, and PGA values for return periods of 475 and 2475 years. |
| Peiris et al. [14]               | The Arabian Gulf including Dubai and Abu Dhabi | Models by Dahle et al. [39] and Atkinson and Boore [33] were applied for the Arabian stable craton, while those by Ambraeys et al. [22] and Sadigh et al. [40] were considered for the Zagros and Makran regions. | Not provided              | Hazard curves for the selected cities, UHS, and PGA values for return periods of 475 and 2475 years. |
| Musson et al. [15]               | The UAE                             | Model by Ambraeys et al. [22] was used for the estimation of SA values, while the Ambraeys [41] model was applied for the prediction of the PGA values. | Not provided              | PGA and SA values for a return period of 475 years.                                        |
| Malkawi et al. [16]              | Fifteen major cities in the UAE     | The model by Atkinson and Boore [33] was applied for the defined source.                   | Haz_ph.exe (FORTRAN Execution File) | Hazard curves, UHS, and PGA maps for a return period of 475 years.                            |
| Aldama-Bustos et al. [17]        | Dubai, Abu Dhabi, and Ras-Al Khaimah (UAE) | Models by Youngs et al. [30] and Atkinson and Boore [31] were used for the Makran subduction zone. Models by Abrahamson and Silva [24], Ambraeys et al. [23], Boore and Atkinson [28], and Akkar and Bommer [27] were applied for the shallow crustal sources. The Atkinson and Boore [34] model was applied to earthquakes within the stable craton. | CRISIS 2007 [42]          | Hazard curves, UHS for return periods of 500, 1000, 2500, 5000, 10000 years, and hazard disaggregation for PGA, SA 0.2, 1.0, 3.0 s for the studied three cities. |
Table 1. Cont.

| The Study            | Study Region                  | Attenuation Relationships                                                                 | Software Code           | Results                                                                                           |
|----------------------|-------------------------------|-------------------------------------------------------------------------------------------|-------------------------|---------------------------------------------------------------------------------------------------|
| Shama [18]           | Dubai (UAE)                   | Models by Atkinson and Boore [33], Gregor et al. [43], Youngs et al. [30] were applied to the “intraslab” western segment of the Makran subduction zone. Models by Abrahamson and Silva [24], Campbell and Bozorgnia [25], and Ambraseys et al. [22] were used for the western segment of the Zendan-Minab-Palami Fault. Finally, models by Abrahamson and Silva [24], Ambraseys et al. [22], and Campbell and Bozorgnia [25] were applied for the Dibba Fault. All these combinations were used within logic-trees. | EZ-FRISK-7.26 [44]     | Hazard curves, and UHS and PGA for return periods of 475 and 2475 years.                           |
| El-Hussain et al. [19]| Sultanate of Oman, and the UAE| Models by Ambraseys et al. [22], Abrahamson and Silva [24], and Boore et al. [45] were applied for earthquakes occurring within the defined active shallow crustal sources. Models by Youngs et al. [30] and Atkinson and Boore [31] were applied for the Makran subduction zone. Additionally, for the Arabian stable craton, the model of Atkinson and Boore [34] was also used. | CRISIS 2007 [42]       | Mean and 84th percentile PGA, and SA (0.1, 0.2, 1.0, and 2.0 s) maps for return periods of 475 and 2475 years. UHS for Dubai, for the previously mentioned return periods were also included. |
| Khan et al. [20]     | The UAE                       | Models by Boore and Atkinson [28], Abrahamson and Silva [24,46], and Campbell and Bozorgnia [47] were assigned to sources covering the Zagros region and Oman Mountains. Models by Atkinson and Boore [31] and Youngs et al. [30] were used for the Makran subduction zone. Atkinson and Boore [34] model was used for earthquakes within the Arabian Craton. | EZ-FRISK V. 7.3 (Risk Engineering Inc.) | Hazard curves for the main cities in the UAE; UHS for different proposed regions for return periods of 475 and 2475 years; PGA and SA (0.2, 1.0, 2.0, 3.0, 4.0 s) maps for the UAE for a return period of 2475 years; and hazard deaggregation (for PGA and SA 1.0 s) for the city of Abu Dhabi for a return period of 2475 years. |
| Al-Shijbi et al. [21] | The Arabian Peninsula         | They applied Akkar and Bommer [26], Chiou and Youngs [29], and Zhao et al. [32] models for the active shallow crustal seismic sources. While, Youngs et al. [30], Atkinson and Boore [31], and Zhao et al. [32] were used for the subduction zones (Makran and Cyprus). Additionally, for the Arabian stable craton, they used Atkinson and Boore [34], and Campbell [35] models in conjunction with equations by Akkar and Bommer [26], Chiou and Youngs [29], and Zhao et al. [32]. | EZ-FRISK (Risk Engineering Inc.) | PGA and SA (0.2, 0.5, 1.0, and 2.0 s) values and maps for return periods of 475, 975 and 2475 years. UHS for several cities, including Dubai and Abu Dhabi, for the previously mentioned return periods were also computed. |
In terms of the implemented seismic source model (Table 1), some of these studies applied a simple and a regional model (e.g., [10,13–16]) in which the ZBFTB, the Makran subduction zone, and the Arabian Gulf Craton (see Figure 1) were considered as a single potential seismic source. Meanwhile, other studies, e.g., [12,17,19–21], tried to delimit different seismic zones differentiating the prevailing seismotectonic environment in their studied regions (see Table 1). Accordingly, a variety of different ground-motion attenuation models were applied in each individual study. Some of the most commonly used models in the previous assessments, for the shallow active crustal regions, were those developed by Ambraseys et al. [22,23], Abrahamson and Silva [24], Campbell and Bozorgnia [25], Akkar and Bommer [26,27], Boore and Atkinson [28], and Chiou and Youngs [29]. The applied models for the active subduction regions were those of Youngs et al. [30], Atkinson and Boore [31], and Zhao et al. [32]. Furthermore, for some assessments that considered the Arabian stable cratonic area, the models by Atkinson and Boore [33,34] and/or Campbell [35] were used.

From the previously-mentioned seismic hazard assessments, applying different source models and attenuation relationships for each individual study, and by using different software codes (see Table 1), different results have been obtained and presented in different forms and formats (e.g., hazard curves, UHS, PGA, and SA values for some spectral periods, with return periods ranging from 100 up to 10000 years).

Great differences in the obtained results from subsequent studies, for the same studied sites, have been observed (e.g., see PGA values for Dubai and Abu Dhabi in Table 2). These differences can be attributed to the following main reasons: (a) the considered earthquake catalog and its completeness, which affects significantly the obtained hazard values especially in regions with moderate seismicity, (b) the seismic source model in relation to the prevailing seismotectonic context of the studied region, and (c) the selection of the most appropriate representative ground-motion attenuation model(s) representing the attenuation characteristics in the region under study.

Table 2. Previously estimated PGA (g) values, for rock-site conditions and a return period of 475 years, for the quoted seismic hazard assessments, which arranged chronologically, for the emirates of Abu Dhabi and Dubai, in comparison with the obtained values in the current study.

| Study                          | Abu Dhabi | Dubai |
|--------------------------------|-----------|-------|
| Abdalla and Al-Homoud [12]    | 0.12      | 0.15  |
| Sigbjornsson and Elnashai [13] | —         | 0.16  |
| Peiris et al. [14]            | 0.04      | 0.06  |
| Musson et al. [15]            | —         | 0.05  |
| Malkawi et al. [16]           | 0.10      | 0.16  |
| Aldama-Bustos et al. [17]     | 0.04      | 0.05  |
| Shama [18]                    | —         | 0.17  |
| El-Hussain et al. [19]        | 0.04      | 0.06  |
| Khan et al. [20]              | 0.035     | 0.047 |
| Al-Shijbi et al. [21]         | 0.033     | 0.047 |
| Current Study                 | 0.05      | 0.09  |

Additionally, there is not a unified and specific seismic design code/regulation applicable for buildings all over the three studied countries. However, hazard assessments could be incorporated into the well-known internationally applied seismic design codes, e.g., [48–50]. The UBC [48] classifies the emirates of Abu Dhabi, Dubai, and the cities of Doha and Manama to be located within Zone 0, which means that they do not need any seismic regulation because there is no “significant” seismic hazard (according to this code). The only exception is that for those tall buildings with more than five stories in the Dubai municipality. They were considered within Zone 2A (PGA value equals to 0.15 g).
defined by the UBC [48]. In contrast to the UBC [48] format, that uses the PGA values as a direct input for the seismic design criteria, the Abu Dhabi municipality has recently adapted the IBC [50] and enforced the ADIBC [7] which depends mainly on the SA values at 0.2 and 1.0 s. This enforced code was based mainly on the IBC [50] regulations published by the International Code Council, considering the regional subdivision of the UAE by Khan et al. [20]. These authors classified the UAE into four main zones, based on a seismic hazard assessment for B soil conditions (NEHRP classification) for the whole country, and for a return period of 2475 (check whole paper) years. The corresponding SA (0.2 s) and SA (1.0 s) pair values (2475 years return period) for the defined zones all over the UAE are equal to 0.21 and 0.07 g, 0.28 and 0.11 g, 0.42 and 0.17 g, and 0.70 and 0.22 g, for zones 1, 2, 3, and 4, respectively. In addition, the Qatar National Construction Standards [9] and earlier editions did not enforce any seismic design requirements for the construction and design of buildings in the country. However, the specifications of the QGOSM [8] suggested that some seismic acceleration values should be adopted for the design of new buildings and structures in the country. The most acceptable design spectra for Qatar are those developed by Peiris et al. [14] and Pascucci et al. [51] for a return period of 2475 years [51].

The previously mentioned building regulations do not provide a unified seismic design regulation nor PGA and SA values specifically for each major city or significant site. Instead, they divide each country (when available) into broad zones, assigning to each of them a single or pair seismic hazard value(s). Therefore, the justification for a new seismic hazard assessment and its subsequent homogenous seismic design maps/values for the countries of UAE, Qatar and Bahrain is a necessity, from our point of view, taking into account all relevant uncertainties in the seismicity parameters and the applied ground-motion attenuation models, and taking advantage of the newly developed earthquake catalog and seismic source model by Sawires et al. [2,6].

3. The Earthquake Catalog

An updated Poissonian earthquake catalog [52–54] as well as a better understanding of the seismotectonic setting in the region under study constitute the fundamental basis to define a reliable and representative seismic source model, which is the first crucial element in order to perform a reliable PSHA. In the current research, a new catalog from the available original data sources was compiled. Thus, a unified catalog in terms of m (spatial extent between 47° and 66° E longitudes, and between 21° and 31° N latitudes), and spanning the time period from 685 to 2019 has been assembled and published by Sawires et al. [2,6]. For its compilation, several published papers, bulletins, and data sources were considered (e.g., published papers [17,19,52–55], the International Seismological Center (ISC) bulletin [56], the global instrumental ISC-GEM catalog [57], the EHB catalog [58], the International Institute of Earthquake Engineering and Seismology and the Iranian Seismological Center [59], the 2014 Seismic Hazard Model for the Middle East “EMME-SHM14” database [60,61] and the United States Geological Survey (USGS) bulletin [62]). During the merging process, it was necessary to avoid any possible duplication for earthquake records from different catalog sources. Differences in origin time less than one minute, and in coordinates less than one degree, have been identified. Such records have been manually examined and the duplicated events were removed. Initial compiled magnitude sizes were described by several scales (surface-wave “Ms”, body-wave “mb”, local “ML and MN”, and moment “Mw” magnitudes). Sawires et al. [2,6] applied some magnitude conversion scaling relationships (Equations (1)–(5)) to unify the recorded magnitudes into moment magnitude. Some of these relationships were developed originally by Shahvar et al. [52] for Central Iran and Zagros regions.

\[
M_w = 0.611(\pm 0.010)M_s + 2.314(\pm 0.047) \quad \text{“} M_s < 6.1\text{”}
\]  

\[
M_w = 0.949(\pm 0.029)M_s + 0.243(\pm 0.192) \quad \text{“} M_s \geq 6.1\text{”}
\]  

\[
M_w = 1.030(\pm 0.017)mb - 0.057(\pm 0.082)
\]
As a following step to remove any dependent (non-Poissonian) earthquake such as foreshocks, aftershocks or earthquake swarms, the authors applied the Gardner and Knopoff [63] procedure to identify those dependent earthquakes. Finally, the completeness of the obtained catalog (Figure 1) has been analyzed, for different magnitude ranges, by plotting the cumulative number of earthquakes above a specific magnitude. Different completeness periods, with different activity rates, have been obtained for both shallow-depth (≤ 35 km) and intermediate-depth (> 35 km) earthquakes. For instance, the catalog for shallow earthquakes was found to be complete for magnitudes above Mw 5.0 and 6.0 since 1945 and 1920, respectively. However, the intermediate-depth events catalog was found to be complete, for the same previous magnitude sizes, only since 1995 and 1975, respectively (for more details, refer to Sawires et al.) [2,6].

4. The Considered Seismic Source Models

The delimitation and characterization of the possible potential seismic sources in the region of interest is another key point for any PSHA [61,64]. Area sources are usually used to delimit the distributed seismicity that could not be associated directly to active faults. In this regard, the estimated seismicity recurrence parameters are assumed to be uniform inside each individually defined source zone. When delineating the possible active source areas, all available information about geology and seismotectonics of the region (focal mechanisms and active faults), as well as seismicity (historical and instrumental), was taken into account [2,64]. In the current assessment, and to consider the uncertainty in the source model, three alternative sets of recently published source models are used in a logic-tree scheme; one of them is a spatially-smoothed seismicity model, and the other two are the area source models developed by El-Hussain et al. [65] and Sawires et al. [2] for the Arabian Peninsula and the surroundings of the UAE (see Figure 2).

The area source model by Sawires et al. [2] was developed specifically for the UAE and its surroundings. Using the previously quoted catalog [6], alongside with available data about active faults in the Zagros and the Makran regions [61], as well as the geology and crustal thickness information [66,67], the authors proposed a new seismic source model consisting of a total of 12 area seismic sources. Those area sources can be categorized into two main groups: crustal shallow-depth (h ≤ 35 km) area sources (from Sh-01 to Sh-10; see Figure 2a), and intermediate-depth (35 < h ≤ 70 km) area sources (IN-01 and IN-02; see Figure 2b). The defined sources cover the possible potential active seismic regions that may contribute to the seismic hazard in the studied countries. The authors delimited the sources Sh-01 (Arabian Gulf), Sh-02 (Foredeep and Mountain Front), Sh-03 (Simple Fold Belt), Sh-04 (High Zagros Thrust Belt), and IN-01 (Zagros Intermediate-depth Earthquakes) to cover the seismicity along the ZBFTB. Additionally, the sources Sh-05 and Sh-06 were delimited specifically to cover the crustal shallow earthquakes along the Nayband-Gowk Fault zone and the Zagros-Makran Transition Zone, respectively (see Figure 2a,b). Furthermore, three different area sources were defined to delimit both crustal and intermediate-depth seismicity along the Makran Subduction Zone (Sh-07 “Western Makran”, Sh-08 “Eastern Makran”, and IN-02 “Makran Intermediate-depth Earthquakes”).

The last shallow crustal area sources were delineated specifically to include the potential seismicity located within the Oman Mountains and Dibba Fault (Sh-09), and the Owen-Murray Fracture zone (Sh-10) (see Figure 2a,b) (for more information about the specific characteristics for each delimited area source, see Sawires et al. [2]). Similar to the Earthquake Model for the Middle East [60,61], the Sawires et al. [2] seismic source model considers the intermediate-depth earthquakes as separate source areas. All related seismicity parameters (annual rate of earthquakes above Mw 4.0, b-value, mean seismogenic depth, and maximum recorded and expected magnitudes), as well as the mean stress regime for the defined seismic sources, have been imported and considered in the current assessment and tabulated in Table 3.
about geology and seismotectonics of the region (focal mechanisms and active faults), as well as seismicity (historical and instrumental), was taken into account [2,64]. In the current assessment, and to consider the uncertainty in the source model, three alternative sets of recently published source models are used in a logic-tree scheme; one of them is a spatially-smoothed seismicity model, and the other two are the area source models developed by El-Hussain et al. [65] and Sawires et al. [2] for the Arabian Peninsula and the surroundings of the UAE (see Figure 2).

Figure 2. The considered two zoning seismic source models in the current assessment. (a) and (b) shallow and intermediate-depth sources, respectively, by Sawires et al. [2], and (c) model by El-Hussain et al. [65].

A second alternative model is a spatially smoothed seismicity model. It was chosen to be used in the current assessment to consider the uncertainty in the knowledge of the boundaries of the previous zoning model, as well as to consider earthquakes where they really happen (e.g., low-magnitude earthquakes occurred in the Arabian cratonic area to the southwest from the defined sources). This model is based on the approach proposed by Frankel [68] to model the distributed seismicity, i.e., the seismicity that cannot be assigned to specific tectonic structures. The employed procedure is detailed on the following. The region was divided into square cells (bins) of $0.1^\circ \times 0.1^\circ$ in size and the number of earthquakes above a certain magnitude was counted inside each cell. In this case we have used the catalog compiled by Sawires et al., [6], and a reference magnitude equal to Mw 5.0 since 1940 for crustal earthquakes, and since 1965 for intermediate-depth events. Thereby, initially, the annual number of events above Mw 5.0 is counted into each cell. From this value, (a) the
annual number of earthquakes above Mw 4.0 into each cell is derived using the Gutenberg-Richter relationship with the corresponding $b$-parameter from the source where the cell is included, and (b) finally, these values are spatially smoothed using a Gaussian filter with a $c$ parameter equals to 0.2°. The selected dates of 1940 and 1965 are considered those for which the Mw 5.0 events can be considered complete for crustal and intermediate-depth events, respectively [2]. The Gaussian filter is used to preserve the total number of earthquakes [68], and the selected $c$ value considers the uncertainty in the earthquake location in this region. This procedure is the same followed by the authors in similar works, for instance, by Peláez and López Casado [69] in all the Iberian Peninsula, Peláez et al. [70] in Algeria, and Peláez et al. [71] in SE Spain. The obtained result, the annual number of earthquakes above magnitude Mw 4.0 in each cell (Figure 3), is considered the input for the seismic hazard assessment when using this approach, where each cell is assumed to be an area source.

$b$-values and maximum magnitudes are the same values as estimated in the Sawires et al. [2] model.

Table 3. Seismicity parameters (average depths, annual rate of earthquakes above Mw 4.0, $b$-value, maximum observed/recorded and maximum expected magnitudes) and stress regime for the model by Sawires et al. [2].

| Source | Depth (km) | $\lambda$ (≥4.0) | $b$-Value | $M_{\text{max}}^{\text{obs}}$ | Date       | $M_{\text{max}}$ | Stress Regime       |
|--------|------------|-------------------|-----------|-----------------------------|------------|-------------------|---------------------|
| Sh-01  | 17.2       | 2.59 ± 0.44       | 0.87 ± 0.31 | 5.9                         | 1956/03/09 | 6.00 ± 0.15      | Pure compressional  |
| Sh-02  | 17.7       | 8.83 ± 0.55       | 0.86 ± 0.10 | 6.7                         | 1703/–/–   | 6.85 ± 0.40      | Pure compressional  |
| Sh-03  | 20.0       | 8.24 ± 0.71       | 0.73 ± 0.15 | 6.8                         | 1440/–/–   | 6.85 ± 0.38      | Pure compressional  |
| Sh-04  | 18.0       | 6.94 ± 0.87       | 1.00 ± 0.11 | 6.6                         | 1990/11/06 | 6.65 ± 0.14      | Pure compressional  |
| Sh-05  | 14.0       | 3.42 ± 0.34       | 0.82 ± 0.04 | 7.2                         | 1981/07/28 | 7.40 ± 0.18      | Pure compressional  |
| Sh-06  | 19.1       | 1.17 ± 0.28       | 0.82 ± 0.06 | 6.2                         | 2013/05/11 | 6.35 ± 0.16      | Compressional strike-slip |
| Sh-07  | 17.4       | 1.93 ± 0.26       | 0.83 ± 0.15 | 6.1                         | 1979/01/10 | 6.20 ± 0.15      | Compressional strike-slip |
| Sh-08  | 24.0       | 3.14 ± 0.35       | 0.76 ± 0.09 | 8.1                         | 1945/11/28 | 8.10 ± 0.30      | Pure compressional  |
| Sh-09  | 15.1       | 0.81 ± 0.16       | 0.84 ± 0.12 | 6.0                         | 1497/–/–   | 6.20 ± 0.28      | Oblique extensive   |
| Sh-10  | 16.9       | 4.82 ± 0.89       | 1.11 ± 0.35 | 5.9                         | 1903/01/14 | 1962/12/26       | Pure compressional  |
|        |            |                   |           |                             | 2008/12/25 | 5.90 ± 0.14      |                     |
| IN-01  | 46.0       | 12.00 ± 1.28      | 1.03 ± 0.09 | 6.6                         | 1999/03/04 | 6.80 ± 0.18      | Strike-slip compressional |
| IN-02  | 49.4       | 2.49 ± 0.37       | 0.86 ± 0.10 | 7.7                         | 2013/04/16 | 7.70 ± 0.30      | Pure extensional    |
additional four sources (Z-54, Z-55, Z-56, and Z-57) were included by the authors to cover the seismicity along the Owen, Murry Ridge, Oman Mountains, and the Arabian Cratonic region, respectively. This last source (Z-57) is acting as a background zone in this assessment in particular, i.e., an area source without any identifiable fault sources, modeling the diffuse seismicity. Used seismicity parameters (seismogenic depth, annual rate of earthquakes above Mw 4.0, b-value, and maximum expected magnitude) are those considered by El-Hussain et al. [65] and listed in Table 4.

The third alternative seismic source model is the one developed by El-Hussain et al. [65] that used before to assess the seismic hazard for the Arabian Peninsula. Among the 57 area sources defined by El-Hussain et al. [65] for the whole Arabian Peninsula, only twenty-two area sources (Figure 2c) have been considered, which can influence the seismic hazard in the studied region. The considered seismic sources, as labelled from the authors, are the following: from 1 to 18, and from 54 to 57 (see Figure 2c). Labelled sources Z-1 (Makran East), Z-2 (Makran Intraplate), Z-3 (Makran West), Z-4 (Jaz-Murian), Z-5 (Zendan Fault), Z-6 (Jiroft Fault), Z-7 (Ali Abad), and Z-8 (Gowk Fault) are covering the seismicity along the Makran subduction zone. However, sources labelled as Z-9 (Arabian Gulf), Z-10 (Zagros Foredeep), Z-11 (Zagros Simple Fold), Z-12 (High Zagros), Z-13 (Sabz-Pushan Fault), Z-14 (Karebas Fault), Z-15 (Kazerun Fault), Z-16 (Borazjan Fault), Z-17 (Dezful Embayment), and Z-18 (Mesopotamia) cover the seismicity along the Zagros region. Finally, an additional four sources (Z-54, Z-55, Z-56, and Z-57) were included by the authors to cover the seismicity along the Owen, Murry Ridge, Oman Mountains, and the Arabian Cratonic region, respectively. This last source (Z-57) is acting as a background zone in this assessment in particular, i.e., an area source without any identifiable fault sources, modeling the diffuse seismicity. Used seismicity parameters (seismogenic depth, annual rate of earthquakes above Mw 4.0, b-value, and maximum expected magnitude) are those considered by El-Hussain et al. [65] and listed in Table 4.

Figure 3. The annual number of earthquakes above Mw 4.0 for each cell/bin that is considered for the spatially-smoothed seismicity model for both crustal (upper plot) and intermediate-depth (lower plot) sources (imported from Sawires et al. [2] model).
Table 4. Seismicity parameters (seismogenic depth, annual rate of earthquakes above Mw 4.0, b-value, maximum expected magnitude) for the model by El-Hussain et al. [65].

| Source | Depth (km) | λ (≥4.0) | b Value | Mmax |
|--------|------------|-----------|---------|------|
| Z-01   | 24.0       | 1.822 ± 0.371 | 0.68 ± 0.06 | 8.40 ± 0.10 |
| Z-02   | 24.0       | 0.860 ± 0.198  | 0.65 ± 0.06 | 7.80 ± 0.30 |
| Z-03   | 32.0       | 0.680 ± 0.167  | 0.72 ± 0.08 | 6.20 ± 0.23 |
| Z-04   | 42.0       | 0.423 ± 0.131  | 0.68 ± 0.09 | 6.80 ± 0.82 |
| Z-05   | 34.0       | 0.465 ± 0.133  | 0.57 ± 0.09 | 6.30 ± 0.22 |
| Z-06   | 28.0       | 1.268 ± 0.271  | 0.74 ± 0.07 | 6.00 ± 0.14 |
| Z-07   | 31.0       | 2.157 ± 0.411  | 0.66 ± 0.06 | 6.80 ± 0.18 |
| Z-08   | 17.0       | 1.602 ± 0.299  | 0.73 ± 0.06 | 7.50 ± 0.34 |
| Z-09   | 17.0       | 1.821 ± 0.368  | 0.76 ± 0.07 | 6.20 ± 0.26 |
| Z-10   | 19.0       | 3.359 ± 0.520  | 0.79 ± 0.05 | 6.80 ± 0.21 |
| Z-11   | 21.0       | 8.820 ± 1.160  | 0.79 ± 0.03 | 6.90 ± 0.21 |
| Z-12   | 22.0       | 3.094 ± 0.468  | 0.76 ± 0.04 | 7.60 ± 0.24 |
| Z-13   | 20.0       | 0.686 ± 0.184  | 0.73 ± 0.08 | 6.30 ± 0.34 |
| Z-14   | 20.0       | 0.314 ± 0.104  | 0.78 ± 0.09 | 5.80 ± 0.46 |
| Z-15   | 20.0       | 1.621 ± 0.417  | 0.69 ± 0.08 | 6.00 ± 0.21 |
| Z-16   | 17.7       | 0.989 ± 0.281  | 0.70 ± 0.08 | 5.80 ± 0.22 |
| Z-17   | 25.0       | 5.340 ± 0.817  | 0.81 ± 0.04 | 6.80 ± 0.12 |
| Z-18   | 27.0       | 1.670 ± 0.263  | 0.93 ± 0.08 | 6.50 ± 0.30 |
| Z-54   | 16.9       | 0.594 ± 0.160  | 0.57 ± 0.08 | 6.80 ± 0.24 |
| Z-55   | 16.9       | 0.559 ± 0.193  | 0.50 ± 0.10 | 6.10 ± 0.25 |
| Z-56   | 15.1       | 0.243 ± 0.080  | 0.83 ± 0.09 | 6.20 ± 0.21 |
| Z-57   | 15.0       | 2.000 ± 0.342  | 0.99 ± 0.06 | 6.60 ± 0.31 |

5. Selected Ground-Motion Attenuation Models

The selection of the ground-motion attenuation model is mainly dependent on the prevailing seismotectonic setting of the region, and on the availability of strong motion data. The strong motion data are very limited in the studied countries. In fact, there is not enough strong motion data to derive a region-specific attenuation model, nor for the calibration of some selected attenuation equations. All the previously mentioned seismic hazard assessments (Table 1) were performed by applying worldwide or regionally adopted ground-motion attenuation model(s) developed for other regions/countries.

Taking into account the prevailing seismotectonic environment, the global ground-motion attenuation models are broadly falling into one of the following categories: (a) active tectonic regions dominant by shallow crustal seismicity, (b) active tectonic regions with subduction zones, and (c) stable continental regions. In the current assessment, and considering the proposed seismic source models and following the global tectonic regionalization model by Chen et al. [72], the delimited potential seismic sources fall into the first two groups: the active shallow crustal and subduction sources.

Since most of the potential seismicity that could contribute to the seismic hazard in the considered countries are located mainly on Iran (the Zagros region and the Makran subduction zone), worldwide as well as region-specific ground-motion attenuation models were preferred to be applied in this assessment. Farhadi et al. [73] assessed the applicability of several ground-motion attenuation models against the local recorded strong-motion data for assessing the seismic hazard in Iran. They initially selected several ground-motion models that developed for different geographic regions (Iran, Turkey,
the Middle East, Europe, the Western United States and Japan), for the active shallow crustal regions. They considered attenuation models from five groups: (a) four models from the North Generation Attenuation-West2 (NGA-West2) Project [74–77], (b) local attenuation models of Iran [78–82], (c) models from Turkey [83,84], (d) two Japanese models [32,85], and (e) models proposed for Europe and the Middle East [86–88]. They evaluated and compared the selected attenuation models against the local database in Iran (643 strong-motion records coming from 240 earthquakes within the magnitude range Mw 3.9 to 7.3, for Joyner–Boore distances up to 300 km). As a final conclusion for this study, the authors recommended the application of the region-specifically developed attenuation models by Sedaghati and Pezeshk [79], Zafarani et al. [81], and Farajpour et al. [82], as well as the regional attenuation models by Zhao et al. [32] and Bindi et al. [87], to assess the seismic hazard, considering the whole strong-motion database. In the current assessment, and taking into account the results from this recent published study, the most recent ground-motion attenuation models by Zafarani et al. [81] and Farajpour et al. [82], alongside the NGA-West2 model proposed by Abrahamson et al. [75], were considered within a logic-tree scheme (Figure 4). They were considered to characterize the attenuation characteristics for the active shallow crustal regions for the considered seismic source models. Additionally, the ground-motion model developed by Zhao et al. [32] was considered for the defined intermediate-depth seismic sources (IN-01 and IN-02, see Figure 2b) proposed in the source model by Sawires et al. [2]. Those selected model [32,75,81,82] were found to be the best compatible ground-motion attenuation models in terms of their magnitude, distance, and period range definitions.

The first selected attenuation model by Zafarani et al. [81] was considered for the active shallow crustal seismic sources (Figure 4). This attenuation model was developed using the Iranian strong-motion database. It was developed to predict the PGA and the pseudospectral accelerations (for 5% damping ratio) for oscillation periods up to 4.0 s. This ground-motion prediction model is accounting the style of faulting and the site conditions according to the European Committee for Standardization EC-8 [89]. The distance measure in this model is the horizontal distance to the surface projection of the rupture plane (the Joyner–Boore distance RJB). It is valid for a moment magnitude range of 4.0 ≤ Mw ≤ 7.3, and for distances up to 200 km. The second considered attenuation model is that developed by Farajpour et al. [82] (Figure 4). It was also developed specifically for Iran. This attenuation model includes PGA and pseudospectral acceleration ordinates (5% damping ratio) for oscillation periods ranging from 0.01 s to 4.0 s. It is valid within a moment magnitude range of 4.8 ≤ Mw ≤ 7.5, and for rupture distances (Rrup) up to 400 km, taking into consideration the faulting mechanisms. In addition, it includes a definition for the soil conditions based on the value of the average shear-wave velocity for the upper 30 m of soil (Vs,30). In the current study, a value of 760 m/s for this parameter has been considered, reflecting the B/C NEHRP boundary site class.
boundary, i.e., the transition between very dense soil and soft rock conditions. The third selected attenuation model is that developed for shallow crustal regions by Abrahamson et al. [75] which considered as one from the NGA-West2 models (Figure 4). This attenuation model is applicable for earthquakes in the range Mw 3.0 to Mw 8.5, at R$_{BB}$ distances up to 300 km, and for PGA and spectral periods from 0.01 to 10.0 s. It includes a regional variability in the source, path, and site effects as well. In favor of using this relationship, for instance, is the fact that NGA-West2 database [90] includes large Iranian events, as the 2003 M 6.6 Bam earthquake, and that several recent seismic hazard studies in low to moderate seismic areas, e.g., [91–93] have considered to use this ground motion prediction equation. The last selected ground-motion model used for the intermediate-depth seismic sources is that published by Zhao et al. [32] (Figure 4). This attenuation model was developed for interface/interplate, inslab/intraslab, and crustal earthquakes, using a strong-motion database from Japan, Iran, and Western United States. It has a valid spectral period range from 0 to 5.0 s, and a valid R$_{rup}$ up to 300 km, within a magnitude range from Mw 5.0 to 8.3. This model also considers the style of faulting, as well as the soil characteristics. In the current assessment, the SCI site class (V$_{S30} > 600$ m/s) has been chosen to be compatible with the previously selected attenuation models.

The ground-motion attenuation models by Zafarani et al. [81], Farajpour et al. [82], and Abrahamson et al. [75] are used together as three alternatives, in a logic-tree framework, to model the ground-motion attenuation for those shallow-depth earthquakes in active crustal regions, sources from Sh-01 to Sh-10 in the Sawires et al. [2] zoning model, and all sources included in the model by El-Hussain et al. [65] (see Figure 2c). For the remaining sources (IN-01 and IN-02 in the model by Sawires et al. [2]), we implemented the model by Zhao et al. [32] for the intermediate-depth seismicity within the Zagros region and the Makran subduction zone (see Figure 5). The compatibility among the four selected ground-motion attenuation models was also considered for the computation of the seismic hazard values. All models are expressed in terms of the moment magnitude. Even though the models by Zafarani et al. [81] and Abrahamson et al. [75] use the R$_{BB}$ distance as a definition for the distance term, while the other two models use the R$_{rup}$ distance, the used software code (R-CRISIS; Ordaz et al. [94]) allows the application of different distance definitions. Thus, no distance conversions are required in the current assessment. Finally, all chosen attenuation models consider different styles for the faulting mechanisms. In this study, the different faulting mechanisms have been considered when using R-CRISIS [94], with the aid of the built-in rupture parameters by Wells and Coppersmith [95], to reflect the tectonic environment of each individual seismic source (see Table 3).

| Seismic Source Model | Gutenberg-Richter b-value | Maximum Expected Magnitude (M$_{max}$) | Ground Motion Attenuation Equations |
|----------------------|---------------------------|--------------------------------------|-----------------------------------|
| Sawires et al. (2019) Smoothed seismicity model: (0.40) | Same as below | Same as below | FPZ19 + Zetal06 (0.33) |
| Sawires et al. (2019) Area source model (0.40) | Same as below | Same as below | ZLLS18 + Zetal06 (0.33) |
| Al-Hussain et al. (2018) Area source model (0.20) | Same as above | Same as above | ASK14 + Zetal06 (0.33) |

Figure 5. Logic-tree design. Considered weights are shown below each individual branch (FPZ19: [82]; Zetal06: [32]; ZLLS18: [81]; ASK14: [75]).
6. Logic Tree Framework and Seismic Hazard Computations

Due to the incomplete understanding of the phenomena of earthquakes, several sources of uncertainties are usually associated with any seismic hazard assessment. In the current assessment, and in order to handle and treat such sources of uncertainties in an appropriate way, a logic-tree design has been implemented. After several considerations for the different input parameters, only four elements/inputs were considered in the logic-tree framework. They are the used seismic source model, the Gutenberg-Richter $b$-value, the maximum expected magnitude, and the used ground-motion attenuation models [75,81,82] for the active shallow crustal regions (Figure 5). In total, 54 branches for the designed logic tree were implemented, with each of them representing an alternative seismic hazard scenario. Considering the seismic source model, three different alternatives have been setup. They are the area source model by Sawires et al. [2], the spatially-smoothed seismicity model using the same catalog and seismicity parameters published by Sawires et al. [2,6], and the area source model by El-Hussain et al. [65] that was used recently by Al-Shijbi et al. [21] and Deif et al. [96] for assessing the seismic hazard for the Arabian Peninsula and Oman, respectively. The assumed subjective weights for the three alternatives are 0.4, 0.4, and 0.2, respectively (Figure 5). A higher weight (0.4) was given to the first couple of models because it is the outcome of the hazard analyst opinion that the model by Sawires et al. [2] is developed specifically and more representative for the region under study rather than the regional model [65] developed for the Arabian Peninsula.

Considering the $b$-value, the same design and weights as in several publications e.g., [19,97] has been followed (Figure 5). The preferred mean $b$-value was given a higher weight (0.6) in comparison with the other two alternatives ($b$-value $\pm \sigma$) with lower weights (0.2). Two additional branches were setup for the third parameter, the maximum expected magnitude, with a given weight of 0.75 (for the mean value) and 0.25 (for $M_{\text{max}} + \sigma$), using in this case a conservative criterion. For the final input element, the selected ground-motion prediction models for the shallow active crustal seismic sources, it is common to apply an equal weight for different branches, e.g., [60,97–99], that represents equal levels of the modeler’s confidence. So, in the current assessment, three equal-weighted branches (0.33 for each) were implemented for the Zafarani et al. [81], the Farajpour et al. [82], and the Abrahamson et al. [75] models (see Figure 5). During the subjective weighting process, we tried as possible to select weights that reflect our confidence in the different input parameters and variables, as well as following some published works, e.g., [19,21,60,97–100].

Based on the Cornell [101] PSHA methodology, the followed seismic hazard assessment procedure in the current appraisal is the standard one. Seismic hazard was computed applying the well-known total probability theorem and expressed in terms of the rate of exceedance for a specific level of ground motion for the considered site condition. Among several available open-source PSHA software codes (e.g., OpenSHA [102], OpenQuake [103], and EqHaz [104]), the validated and verified R-CRISIS [94] was chosen for this assessment. R-CRISIS [94] provides a friendly graphical interface environment to facilitates data input and compute the seismic hazard. The computations were performed for grid points covering all the studied region at a spacing of 0.1° × 0.1° (about 10 km × 10 km). In order to run the assessment, several input parameters for each individual seismic source (and accordingly in each logic-tree branch) were necessary to be included in R-CRISIS [94]. They are: (a) the minimum magnitude ($M_{\text{min}}$) that should be defined in the integration process, which we considered to be equal to Mw 4.0 in our assessment for all included seismic sources (considered as the appropriate magnitude to be used in a good design and construction of buildings e.g., [105]), (b) the annual rate of occurrence for earthquakes of magnitudes equal to or greater than the $M_{\text{min}}$, (c) the Gutenberg-Richter $\beta$-value ($\beta = b \times \ln(10)$), and finally, (d) the maximum expected magnitude for each source. Additionally, coefficients of variation for the $\beta$ values and the standard deviations for the $M_{\text{max}}$ values were also included to account for the epistemic uncertainties (see Tables 3 and 4). In order to implement the chosen ground-motion attenuation models into the software, R-CRISIS [94] allows only three categories of attenuation relationships. They are the attenuation tables that could be provided by the analyst, the built-in attenuation models, and the generalized attenuation models. For this current assessment,
two attenuation tables for the models by Zafarani et al. [81] and Farajpour et al. [82] were prepared and built following the guided structure defined in, and compatible with, the R-CRISIS [94] software. Additionally, the other two models by Abrahamson et al. [75] and Zhao et al. [32] were defined using a built-in attenuation relationship.

The obtained ground-motion values in the current assessment are presented for two different probabilities of exceedance: 10% in 50 years (475-year return period), and 5% in 50 years (975-year return period), both for the considered site conditions (B/C NEHRP boundary). Seismic hazard results are presented in a series of contour maps (Figure 6) of peak ground horizontal acceleration, and spectral accelerations (for a 5% damping ratio) at periods of 0.2 s and 1.0 s, for each probability of exceedance. The selection of those depicted oscillation periods is considered because of the fact that the hazard values for 0.2 s and 1.0 s spectral periods are greatly representative for the overall shape of the UHS. Additionally, these two values for the spectral periods permit the application of the Malhotra [106] criterion (based on the procedure by Newmark and Hall [107]) to propose a design spectrum for each studied site.

Figure 6. Seismic-hazard maps, for B/C NEHRP boundary site conditions, depicting the mean PGA and spectral accelerations [SA (0.2 s), and SA (1.0 s)] for return periods of 475 and 975 years [AAN, Al-Ain, ABD, Abu Dhabi; AJM, Ajman; DOH, Doha; DUB, Dubai; FUJ, Fujaira; MAN, Manama; RAK, Ras Al-Khaimah; SHJ, Sharjah; UAQ, Umm Al-Quwain].
In addition, the seismic hazard results are presented for ten selected emirates and cities (eight major emirates in the UAE, and the two capital cities of Qatar and Bahrain) in terms of hazard curves (Figure 7) for PGA, as well as their UHS in Figure 8. Two horizontal lines on the hazard curves plots (Figure 7) are highlighting the two considered return periods (475 and 975 years). The choice of those significant cities is mainly based on their geographic distribution, population density, and their socio-economic importance in the UAE, Qatar, and Bahrain. As a result of the computed hazard curves and UHS, different characteristic seismic hazard values (mean PGA, SA\(_{\text{max}}\), SA (0.2 s), and SA (1.0 s)) for the studied cities were derived and listed in Table 5.

Finally, seismic hazard values were deaggregated in terms of distance and magnitude (Figure 9), following Bazzurro and Cornell [108] methodology. For each city, the deaggregation was computed and depicted for four spectral periods (PGA, SA (0.2 s), SA (1.0 s), and SA (2.0 s)) for a return period of 475 years, which is usually considered as input for the seismic design of buildings all over the world. Magnitude bins of 0.5 (from Mw 4.0 to 8.0) and distance intervals of 25 km (from 0 to 400 km) were defined using R-CRISIS [94] software and following the USGS guiding procedure by Harmsen et al. [109]. Accordingly, the contribution (%) of the different earthquake scenarios to the total obtained seismic hazard value, at a specific site, was computed and plotted (see Table 6 and Figure 9). Thus, it allows the identification of what is called by the design [110], the control [111], the dominant [108], or the modal [112] earthquake (see Table 6). This control earthquake is usually defined by the modal or mean value for both magnitude and source-to-site distance (Table 6). The mean value is not always representing a realistic hazard scenario, because the modal value corresponds to the distance-magnitude group that defines the largest contribution to the seismic hazard at a site, hence, corresponding to a more realistic source [113]. Following the estimation and comparison of the modal and mean values, at each individual site, it is possible to determine the sources that mainly contribute to the hazard at that site whether they are only one, or many sources at different distances [69,100]. Table 6 shows the obtained deaggregation results for the four studied spectral periods, at the selected cities and emirates, in terms of both the mean and modal values.
In addition, the SA (0.2 s) values are equal to 0.30 g, 0.28 g, 0.29 g, and 0.26 g for these four emirates, respectively, for the same return period. The cities of Manama and Doha and the emirate of Abu Dhabi are exhibiting the lower PGA (0.06 g, 0.06 g, and 0.05 g, respectively), and SA (0.2 s) values (0.14 g, 0.13 g and 0.12 g, respectively), for the same return period. Finally, the emirates of Sharjah, Dubai and Al-Ain are characterized by in-between PGA (0.10 g, 0.09 g, and 0.07 g, respectively), and SA (0.2 s) values (0.25 g, 0.22 g, and 0.15 g, respectively), for the same return period. Additional seismic hazard values (for 475 and 975 years as return period, and for the considered site conditions) are tabulated for the selected major emirates and cities in Table 5. It depicts the obtained PGA, the maximum spectral acceleration (SA max) and its corresponding natural period (T max), SA (0.2 s), and SA (1.0 s) values for the selected sites. Those obtained seismic hazard values will provide a solid basis for the subsequent studies for site effects, as well as the estimation of the fundamental frequency and amplification factors for different soil profiles at any particular location.

Figure 8. UHS and proposed Malhotra [106] design spectra, both for 5% damping ratio, for B/C NEHRP boundary site conditions and for return periods of 475 and 975 years, in comparison with the available building code regulations.
Table 5. Obtained seismic hazard values for the selected emirates and cities, for return periods of 475 and 975 years [PGA: peak ground acceleration; SA<sub>max</sub>: maximum spectral acceleration; T<sub>max</sub>: spectral period related to SA<sub>max</sub>].

| Country       | Emirate/City | 475 Years | 975 Years |
|---------------|--------------|-----------|-----------|
|               | Mean PGA (g) | 90th PGA (g) | SA<sub>max</sub> (g) | T<sub>max</sub> (s) | SA-0.2 s (g) | SA-1.0 s (g) | Mean PGA (g) | 90th PGA (g) | SA<sub>max</sub> (g) | T<sub>max</sub> (s) | SA-0.2 s (g) | SA-1.0 s (g) |
| United Arab Emirates | RAK       | 0.13       | 0.18       | 0.31       | 0.15       | 0.30       | 0.07       | 0.16       | 0.22       | 0.44       | 0.15       | 0.42       | 0.08       |
|                  | UAQ       | 0.12       | 0.19       | 0.31       | 0.15       | 0.29       | 0.05       | 0.16       | 0.26       | 0.44       | 0.15       | 0.42       | 0.08       |
|                  | AJM       | 0.11       | 0.17       | 0.27       | 0.15       | 0.26       | 0.06       | 0.14       | 0.21       | 0.38       | 0.15       | 0.37       | 0.07       |
|                  | SHJ       | 0.10       | 0.16       | 0.25       | 0.15/0.20  | 0.25       | 0.05       | 0.13       | 0.19       | 0.36       | 0.15       | 0.34       | 0.07       |
|                  | DUB       | 0.09       | 0.14       | 0.22       | 0.15/0.20  | 0.22       | 0.05       | 0.12       | 0.17       | 0.31       | 0.15/0.20  | 0.31       | 0.06       |
|                  | FUJ       | 0.13       | 0.18       | 0.30       | 0.15       | 0.28       | 0.05       | 0.17       | 0.25       | 0.46       | 0.15       | 0.42       | 0.07       |
|                  | AAN       | 0.07       | 0.13       | 0.15       | 0.15/0.20  | 0.15       | 0.03       | 0.10       | 0.17       | 0.22       | 0.15       | 0.21       | 0.04       |
|                  | ABD       | 0.05       | 0.08       | 0.12       | 0.20       | 0.12       | 0.03       | 0.07       | 0.09       | 0.16       | 0.20       | 0.16       | 0.04       |
| Qatar           | DOH       | 0.06       | 0.08       | 0.13       | 0.20       | 0.13       | 0.03       | 0.07       | 0.09       | 0.17       | 0.20       | 0.17       | 0.07       |
| Bahrain         | MAN       | 0.06       | 0.09       | 0.14       | 0.20       | 0.14       | 0.04       | 0.08       | 0.12       | 0.18       | 0.20       | 0.18       | 0.05       |

AAN, Al-Ain; ABD, Abu Dhabi; AJM, Ajman; DOH, Doha; DUB, Dubai; FUJ, Fujaira; MAN, Manama; RAK, Ras Al-Khaimah; SHJ, Sharjah; UAQ, Umm Al-Quwain.
Figure 9. Seismic hazard deaggregation plots, for B/C NEHRP boundary site condition, for a return period of 475 years and for the selected spectral periods.
Table 6. Mean and modal seismic hazard deaggregation results (for magnitude and distance) for a return period of 475 years, for the studied emirates and cities, and for the different spectral periods [PGA, SA (0.2 s), SA (1.0 s), and SA (2.0 s)].

| Emirate /City * | PGA | SA (0.2 s) | SA (1.0 s) | SA (2.0 s) |
|-----------------|-----|------------|------------|------------|
|                 | Modal | Mean | Modal | Mean | Modal | Mean | Modal | Mean |
|                 | Mw/D | Mw/D | Mw/D | Mw/D | Mw/D | Mw/D | Mw/D | Mw/D |
| RAK             | 5.5–6.0 | 50–75 | 5.6 | 94 | 4.5–5.0 | 50–75 | 5.3 | 88 | 6.0–6.5 | 50–75 | 6.5 | 163 | 7.0–7.5 | 200–225 | 6.8 | 189 |
| UAQ             | 5.5–6.0 | 75–100 | 5.6 | 112 | 4.5–5.0 | 50–75 | 5.3 | 102 | 5.5–6.0 | 75–100 | 6.5 | 188 | 7.0–7.5 | 200–225 | 6.8 | 212 |
| AJM             | 5.5–6.0 | 75–100 | 5.6 | 128 | 4.5–5.0 | 75–100 | 5.2 | 115 | 7.0–7.5 | 200–225 | 6.5 | 203 | 7.0–7.5 | 200–225 | 6.8 | 225 |
| SHJ             | 5.5–6.0 | 75–100 | 5.6 | 136 | 4.5–5.0 | 75–100 | 5.2 | 121 | 7.0–7.5 | 225–250 | 6.5 | 210 | 7.0–7.5 | 225–250 | 6.8 | 232 |
| DUB             | 5.5–6.0 | 75–100 | 5.6 | 149 | 4.5–5.0 | 75–100 | 5.2 | 133 | 7.0–7.5 | 225–250 | 6.5 | 221 | 7.0–7.5 | 275–300 | 6.8 | 242 |
| FUJ             | 4.0–4.5 | 0–25 | 5.1 | 35 | 4.5–5.0 | 0–25 | 5.1 | 39 | 5.5–6.0 | 0–25 | 6.2 | 159 | 7.0–7.5 | 275–300 | 6.7 | 215 |
| AAN             | 5.5–6.0 | 100–125 | 5.7 | 235 | 4.5–5.0 | 100–125 | 5.1 | 214 | 7.0–7.5 | 350–375 | 6.4 | 305 | 7.0–7.5 | 300–325 | 6.8 | 322 |
| ABD             | 5.5–6.0 | 275–300 | 5.5 | 237 | 4.5–5.0 | 150–175 | 5.0 | 212 | 7.0–7.5 | 350–375 | 6.5 | 302 | 7.0–7.5 | 350–375 | 6.8 | 318 |
| DOH             | 4.5–5.0 | 75–100 | 5.4 | 216 | 4.0–4.5 | 75–100 | 5.0 | 189 | 7.0–7.5 | 350–375 | 6.5 | 307 | 7.0–7.5 | 350–375 | 6.8 | 324 |
| MAN             | 5.5–6.0 | 225–250 | 5.7 | 259 | 4.5–5.0 | 150–175 | 5.1 | 235 | 7.0–7.5 | 375–400 | 6.5 | 305 | 7.0–7.5 | 375–400 | 6.9 | 316 |

* AAN, Al-Ain; ABD, Abu Dhabi; AJM, Ajman; DOH, Doha; DUB, Dubai; FUJ, Fujaira; MAN, Manama; RAK, Ras Al-Khaimah; SHJ, Sharjah; UAQ, Umm Al-Quwain.
7. Results and Discussion

The isoacceleration maps (Figure 6) highlight the hazard in the northeastern edge of the UAE (the emirates of Ras Al-Khaimah, Umm Al-Quwain, Fujaira, Ajman, Sharjah, and Dubai), as the area that has a relatively higher seismic hazard values than the rest of the studied region (the emirates of Al-Ain and Abu Dhabi, as well as the cities of Doha and Manama) in the context of a low seismic hazard region. The depicted hazard maps show the same contour line pattern, as they have a decreasing value towards the southwest, which is greatly expected; the far the distance from the most active seismic sources, the lower seismic hazard. For a 10% probability of exceedance in 50 years, the northeastern region has seismic hazard values up to 0.13, 0.30, and 0.07 g for the mean PGA, SA (0.2 s), and SA (1.0 s), respectively. In this area, the emirates of Ras Al-Khaimah, Fujaira, Umm Al-Quwain, and Ajman share approximately the same PGA value (0.13 g for the first two emirates, and 0.12 g and 0.11 g, for the third and fourth ones, respectively) for a return period of 475 years (Table 5). In addition, the SA (0.2 s) values are equal to 0.30 g, 0.28 g, 0.29 g, and 0.26 g for these four emirates, respectively, for the same return period. The cities of Manama and Doha and the emirate of Abu Dhabi are exhibiting the lower PGA (0.06 g, 0.06 g, and 0.05 g, respectively), and SA (0.2 s) values (0.14 g, 0.13 g and 0.12 g, respectively), for the same return period. Finally, the emirates of Sharjah, Dubai and Al-Ain are characterized by in-between PGA (0.10 g, 0.09 g, and 0.07 g, respectively), and SA (0.2 s) values (0.25 g, 0.22 g, and 0.15 g, respectively), for the same return period. Additional seismic hazard values (for 475 and 975 years as return period, and for the considered site conditions) are tabulated for the selected major emirates and cities in Table 5. It depicts the obtained PGA, the maximum spectral acceleration (SA_{max}) and its corresponding natural period (T_{max}), SA (0.2 s), and SA (1.0 s) values for the selected sites. Those obtained seismic hazard values will provide a solid basis for the subsequent studies for site effects, as well as the estimation of the fundamental frequency and amplification factors for different soil profiles at any particular location.

Another interesting output results from this assessment are the UHS. In Figure 8, the UHS for a 475 years return period, in comparison with the available seismic design regulations, as well as a proposed design spectrum based on Malhotra [106] criterion, are plotted. For each given spectrum, a number of 15 spectral ordinates have been computed in detail during the analysis. They are 0.0 (PGA), 0.04, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40, 0.50, 0.70, 1.0, 1.5, 2.0, 3.0, and 4.0 s. From the displayed UHS in Figure 8, the greatest obtained seismic hazard values (SA_{max}) for a 475-year return period were obtained for the emirates of Ras Al-Khaimah, Umm Al-Quwain, Fujaira, Ajman, and Sharjah (0.31 g, 0.31 g, 0.30 g, 0.27 g, and 0.25 g, respectively), while the lowest ones were obtained for the emirate of Abu Dhabi (0.12 g). In addition, as can be observed in Figure 8 and Table 5, the corresponding natural periods (T_{max}) for the SA_{max} were observed at natural periods of 0.15–0.20 s (usually, they correspond to buildings of three- to four-stories).

There are clear differences between the obtained UHS in the current assessment and those elastic response spectra considered as design spectra in the regulations by the governmental agencies in each country. Relatively higher seismic hazard values for those cities (Dubai and Doha; see Figure 8) than those included in the available regulations that are officially enforced by these municipalities have been obtained. Such differences can be attributed to several factors: (a) a more updated earthquake catalog (until 2019) than those studies considered in the building regulations for the investigated countries has been used, (b) the different zoning models (three alternative source models weighted in a logic-tree design) implemented in our assessment, (c) the inclusion in this assessment of two different levels of seismicity, and corresponding potential seismic sources, in which the intermediate-depth seismicity was discriminated from the shallower one, and finally, (d) the selected ground-motion attenuation models used in this assessment are worldwide and region-specific models, differing from those considered in previous studies.

Taking into consideration such differences, as well as the fact that some regulations for some emirates and cities only depend on the PGA value in the definition of the design spectra, we propose the application of a different approach for the formulation of the design spectra all over the studied
countries. It can be defined using only two SA values (SA (0.2 s) and SA (1.0 s)). This approach was proposed by Malhotra [106] based on the Newmark and Hall [107] procedure for the definition of a design spectrum, and following the same methodology as in the published works by Hamdache et al. [114] for Northern Algeria and Sawires et al. [97] for Egypt. First, the so-called control period \( T_s \) should be computed from the relationship between the SA (0.2 s) and SA (1.0 s) values obtained from the UHS, as the following:

\[
T_s = \frac{SA(1.0s)}{SA(0.2s)} \cdot 1s
\]

Next, the design spectrum is computed using the following equation:

\[
SA(T) = \begin{cases} 
0.4 \cdot SA(0.2s) + 3.0 \cdot SA(0.2s) \cdot \frac{T}{T_s} & T \leq 0.2 \cdot T_s \\
SA(0.2s) & 0.2 \cdot T_s < T < T_s \\
SA(1.0s) \cdot \frac{T}{T_s} & T > T_s 
\end{cases}
\]

The proposed design spectra clearly show a better agreement with the computed UHS for the selected cities (see Figure 8). The reason is that the SA values at 0.2 and 1.0 s, clearly are representative to a great extent of the overall shape of the UHS.

A final result from the current assessment is the seismic hazard deaggregation, for 475 years as return period, for four spectral periods, and depicted as bar charts for both magnitude and focal distance cells against the obtained hazard contribution (Figure 9). Each bar reflects a different earthquake scenario. The height of each bar is representative to the relative contribution of a specific earthquake scenario to the total obtained seismic hazard at the specific site. From the careful inspection of the displayed hazard deaggregation results in Figure 9 and the tabulated values for the modal and mean distance and magnitude values in Table 6, the selected emirates and cities could be categorized into two main groups.

The first category consists of five emirates (Ras Al-Khaimah, Umm Al-Quwain, Ajman, Sharjah, and Dubai; see Figure 9), in which the shape of the deaggregation plots is characterized by a unimodal single-lobe distribution, in which the maximum (modal) peak is relatively close to the studied emirate, while the tail includes the more distant earthquakes. This means that the seismic hazard at the studied location is due to the closest potential seismic sources. In such case, both the mean and the modal value for the control earthquake nearly coincide. Range values of 94–149 km and 88–133 km (Table 6) were obtained for the mean distances for the control earthquake, for this group of emirates, for PGA and SA (0.2 s), respectively, taking into account the fact that the longer period of ground motion, the more contribution of distant earthquake is expected. For longer periods (SA (1.0 s) and SA (2.0 s)), the mean distance ranges for the control earthquake are reaching 163–221 km and 189–242 km, respectively. However, for the second and last group of emirates and cities (Fujaira, Al–Ain, Abu Dhabi, Doha, and Manama; Figure 9), the deaggregation results show mainly a main lobe for the smaller ground-motion ordinates (PGA and SA (0.2 s)), while a secondary one started to exaggerate for the largest ground-motion ordinates (SA (1.0 s) and SA (2.0 s)). In such a case, the secondary lobes appear to be more significant (for the larger periods) than the primary one. This means that this category of cities is affected by far potential seismic sources (distances of more than 300 km) that could be attributed to the ZBFTB or the Makran subduction zone. Taking into account the characteristics of the considered ground-motion attenuation models, the effect of the very distant earthquakes could be underestimated in this case, specifically for the SA (1.0 s) and SA (2.0 s). Some differences between the obtained modal and mean values could be noticeable for the control earthquake at each studied site (Table 6). Mean value ranges of 35–259 km, 39–235 km, 159–307 km, and 215–324 km were obtained for the mean distances of the control earthquake, for PGA, SA (0.2 s), SA (1.0 s), and SA (2.0 s), respectively, for those emirates and cities (Table 6).
8. Summary and Conclusions

The current assessment presents an up-to-date probabilistic seismic hazard study for the UAE, Qatar, and Bahrain. In this analysis, an attempt to achieve an improvement in the seismic hazard with the help of an updated, unified, and Poissonian earthquake catalog, as well as a new updated seismic source model, has been carried out. Additionally, the consideration of three alternative source models throughout the application of a logic-tree scheme, as well as the selection of ground-motion attenuation models was accomplished. The hazard results have been presented in terms of PGA and SA values and contour maps, for a 10% and 5% probability of exceedance in 50 years (return periods of 475 and 975 years, respectively), for the B/C NEHRP boundary site conditions, for the whole studied region. In addition, hazard curves, UHS, and hazard deaggregation for selected significant emirates and cities were specifically derived in comparison with the officially enforced regulations at each individual site. In addition, a design spectrum, based on the SA (0.2 s) and SA (1.0 s) values, has been proposed as a uniform regulation for the seismic design for the studied region.

Significant differences have been observed when comparing the output results from this assessment (UHS for a return period of 475 years) with those available regulations considered by the local authorities (elastic response spectrum) responsible for the seismic design. Thus, a change in the seismic design representation, the seismic hazard results, as well as the recommendation of taking into consideration the new proposed design spectra in the building regulations for the studied countries is advisable. Reflecting the recent scientific advances in the delimitation and characterization of possible potential seismic sources, the consideration of representative ground-motion attenuation models, and application of up-to-date seismic hazard-engineering concepts, we are confident that this assessment represents a clear improvement of the seismic input for the three countries. This assessment also provides the necessary seismic hazard data in a compatible format with the requirements of new building codes. It is worth noting that once more information relevant to the seismicity and seismotectonics is available, more seismic hazard studies should be conducted in the region.

Author Contributions: Conceptualization, R.S. and J.A.P.; methodology, R.S. and J.A.P.; software, R.S.; validation, R.S.; formal analysis, R.S. and J.A.P.; investigation, R.S., J.A.P., and M.H.; resources, R.S.; data curation, R.S. and J.A.P.; writing—original draft preparation, R.S.; writing—review and editing, R.S., J.A.P., and M.H.; visualization, R.S.; supervision, J.A.P.; project administration, R.S.; funding acquisition, J.A.P. All authors have read and agreed to the published version of the manuscript.

Funding: The second author is grateful for receiving partial financial support for this research work through the Programa Operativo FEDER Andalucía 2014-2020—Call by the University of Jaén, 2018.

Acknowledgments: We would like to thank M.A. Santoyo (Institute of Geophysics, UNAM, Mexico) who reviewed the English language of the manuscript. We would like to thank two anonymous reviewers for their thoughtful remarks and invaluable comments.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Johnson, P. Tectonic Map of Saudi Arabia and Adjacent Areas; Technical Report USGS-TR-98-3 (IR 948); United States Geological Survey: Reston, VA, USA, 1998.
2. Sawires, R.; Pelaez, J.A.; AlHamaydeh, M.; Henares, J. A state-of-the-art seismic source model for the United Arab Emirates. J. Asian Earth Sci. 2019, 186, 104063. [CrossRef]
3. Jackson, J.; McKenzie, D. Active tectonics of the Alpine-Himalayan Belt between western Turkey and Pakistan. Geophys. J. R. Astron. Soc. 1984, 77, 185–264. [CrossRef]
4. Bayer, R.; Chery, J.; Tatar, M.; Vernant, P.; Abbassi, M.; Masson, F.; Nillfouroskan, F.; Doerflinger, E.; Regard, V.; Bellier, O. Active deformation in Zagros-Makran transition zone inferred from GPS measurements. Geophys. J. Int. 2006, 165, 373–381. [CrossRef]
5. Fournier, M.; Chamot-Rooke, N.; Petit, C.; Fabbrì, O.; Huchon, P.; Maillot, B.; Lepvrier, C. In situ evidence for dextral active motion at the Arabia-India plate boundary. Nat. Geosci. 2008, 1, 94–98. [CrossRef]
6. Sawires, R.; Peláez, J.A.; AlHamaydeh, M.; Henares, J. Up-to-date earthquake and focal mechanism solutions datasets for the assessment of seismic hazard in the vicinity of the United Arab Emirates. *Data Br.* 2020, 28. [CrossRef]

7. Department of Municipal Affairs. *The Code Handbook: Abu Dhabi International Building Code*; Department of Municipal Affairs: Adu Dhabi, UAE, 2011.

8. Qatar General Organization for Standards and Meterology. *Qatar National Construction Standards*; QGOSM: Doha, Qatar, 2014.

9. Qatar General Organization for Standards and Meterology. *Qatar National Construction Standards*; QGOSM: Doha, Qatar, 2010.

10. Al-Haddad, M.; Siddiqi, G.H.; Al-Zaid, R.; Arafah, A.; Necioglu, A.; Turkelli, N. A Basis for Evaluation of Seismic Hazard and Design Criteria for Saudi Arabia. *Earthq. Spectra* 1994, 10, 231–258. [CrossRef]

11. Grünthal, G.; Bosse, C.; Sellami, S.; Mayer-Rosa, D.; Giardini, D. Compilation of the GSHAP regional seismic hazard for Europe, Africa and the Middle East. *Ann. Geofis.* 1999, 42, 1215–1223. [CrossRef]

12. Abdalla, J.A.; Al-Hoomoud, A. Earthquake Hazard Zonation of Eastern Arabia. In Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, BC, Canada, 1–6 August 2004; p. 9.

13. Sigbjornsson, R.; Elbashashy, A.S. Hazard assessment of Dubai, United Arab Emirates, for close and distant earthquakes. *J. Earthq. Eng.* 2006, 10, 749–773. [CrossRef]

14. Peiris, N.; Free, M.; Lukowski, Z.; Hussein, A.T. Seismic hazard and seismic design requirements for the Arabian Gulf region. In Proceedings of the First European Conference on Earthquake Engineering and Seismology, Geneva, Switzerland, 3–8 September 2006.

15. Musson, R.; Northmore, K.; Sargeant, S.; Phillips, E.; Boon, D.; Long, D.; McCue, K.; Ambraseys, N.N. *The Geology and Geophysics of the United Arab Emirates*; Ministry of Energy: Abu Dhabi, UAE, 2006.

16. Malkawi, A.I.H.; Barakat, S.A.; Shanableh, A.; Al Bdour, W.M.; Omar, M.; Altoubat, S. *Seismic Hazard Assessment and Mitigation of Earthquake Risk in United Arab Emirates*; Jordan University of Science and Technology: Ar-Ramtha, Jordan; University of Sharjah: Sharjah, UAE, 2007.

17. Aldama-Bustos, G.; Bommer, J.J.; Fenton, C.H.; Stafford, P.J. Probabilistic seismic hazard analysis for rock sites in the cities of Abu Dhabi, Dubai and Ra’s Al Khaymah, United Arab Emirates. *Georisk* 2009, 3, 1–29. [CrossRef]

18. Shama, A.A. Site specific probabilistic seismic hazard analysis at Dubai Creek on the west coast of UAE. *Earthq. Eng. Eng. Vib.* 2011, 10, 143–152. [CrossRef]

19. El-Hussain, I.; Deif, A.; Al-Jabri, K.; Toksoz, N.; El-Hady, S.; Al-Hashmi, S.; Al-Toubi, K.; Al-Shijbi, Y.; Al-Sa‘ifi, M.; Kuleli, S. Probabilistic seismic hazard maps for the sultanate of Oman. *Nat. Hazards* 2012, 64, 173–210. [CrossRef]

20. Khan, Z.; El-Emam, M.; Irfan, M.; Abdalla, J. Probabilistic seismic hazard analysis and spectral accelerations for United Arab Emirates. *Nat. Hazards* 2013, 67, 569–589. [CrossRef]

21. Al-Shijbi, Y.; El-Hussain, I.; Deif, A.; Al-Kalbani, A.; Mohamed, A.M.E. Probabilistic Seismic Hazard Assessment for the Arabian Peninsula. *Pure Appl. Geophys.* 2018, 176, 1503–1530. [CrossRef]

22. Ambraseys, N.N.; Simpson, K.A.; Bommer, J.J. Prediction of horizontal response spectra in Europe. *Earthq. Eng. Struct. Dyn.* 1996, 25, 371–400. [CrossRef]

23. Ambraseys, N.N.; Douglas, J.; Sarma, S.K.; Smit, P.M. Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the middle east: Horizontal peak ground acceleration and spectral acceleration. *Bull. Earthq. Eng.* 2005, 3, 1–53. [CrossRef]

24. Abrahamson, N.A.; Silva, W.J. Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismol. Res. Lett.* 1997, 68, 94–109. [CrossRef]

25. Campbell, K.W.; Bozorgnia, Y. Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bull. Seismol. Soc. Am.* 2003, 93, 314–331. [CrossRef]

26. Akkar, S.; Bommer, J.J. Empirical equations for the prediction of PGA, PGV, and spectral accelerations in Europe, the mediterranean region, and the Middle East. *Seismol. Res. Lett.* 2010, 81, 195–206. [CrossRef]

27. Akkar, S.; Bommer, J.J. Empirical prediction equations for peak ground velocity derived from strong-motion records from Europe and the Middle East. *Bull. Seismol. Soc. Am.* 2007, 97, 511–530. [CrossRef]
28. Boore, D.M.; Atkinson, G.M. Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s. *Earthq. Spectra* 2008, 24, 99–138. [CrossRef]
29. Chiou, B.S.J.; Youngs, R.R. An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra. *Earthq. Spectra* 2008, 24, 173–215. [CrossRef]
30. Youngs, R.R.; Chiou, S.-J.; Silva, W.J.; Humphrey, J.R. Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquakes. *Seismol. Res. Lett.* 1997, 68, 58–73. [CrossRef]
31. Atkinson, G.M.; Boore, D.M. Empirical Ground-Motion Relations for Subduction-Zone Earthquakes and Their Application to Cascadia and Other Regions. *Bull. Seismol. Soc. Am.* 2003, 93, 1703–1729. [CrossRef]
32. Zhao, J.X.; Zhang, J.; Asano, A.; Ohno, Y.; Oouchi, T.; Takahashi, T.; Ogawa, H.; Irikura, K.; Thio, H.K.; Somerville, P.G.; et al. Attenuation relations of strong ground motion in Japan using site classification based on predominant period. *Bull. Seismol. Soc. Am.* 2006, 96, 898–913. [CrossRef]
33. Atkinson, G.M.; Boore, D.M. Some comparisons between recent ground-motion relations. *Seismol. Res. Lett.* 1997, 68, 24–38. [CrossRef]
34. Atkinson, G.M.; Boore, D.M. Erratum: Earthquake ground-motion prediction equations for eastern North America. *Bull. Seismol. Soc. Am.* 2007, 97, 1032. [CrossRef]
35. Campbell, K.W. Prediction of Strong Ground Motion Using the Hybrid Empirical Method and Its Use in the Development of Ground-Motion (Attenuation) Relations in Eastern North America. *Bull. Seismol. Soc. Am.* 2003, 93, 1012–1033. [CrossRef]
36. Zare, M. *Attenuation Relation and Coefficients of Movement in Iran*; International Institute of Earthquake Engineering and Seismology: Tehran, Iran, 2002.
37. McGuire, R.K. *FORTRAN Computer Program for Seismic Risk Analysis*; United States Geological Survey: Reston, VA, USA, 1976.
38. Simpson, K. *Attenuation of Strong Ground-Motion Incorporating Near-Surface Foundation Conditions*; London University: London, UK, 1996.
39. Dahle, A.; Bungum, H.; Kvaamme, L.B. Attenuation models inferred from intraplate earthquake recordings. *Earthq. Eng. Struct. Dyn.* 1990, 19, 1125–1141. [CrossRef]
40. Sadigh, K.; Chang, C.-Y.; Egan, J.A.; Makdisi, F.; Youngs, R.R. Attenuation Relationships for Shallow Crustal Earthquakes Based on California Strong Motion Data. *Seismol. Res. Lett.* 1997, 68, 180–189. [CrossRef]
41. Ambraseys, N.N. The prediction of earthquake peak ground acceleration in europe. *Earthq. Eng. Struct. Dyn.* 1995, 24, 467–490. [CrossRef]
42. Ordaz, M.; Aguilar, A.; Arboleda, J. *CRISIS2007. Program for Computing Seismic Hazard*; UNAM Institute of Engineering: Mexico City, Mexico, 2007.
43. Gregor, N.J.; Silva, W.J.; Wong, I.G.; Youngs, R.R. Ground-motion attenuation relationships for Cascadia subduction zone megathrust earthquakes based on a stochastic finite-fault model. *Bull. Seismol. Soc. Am.* 2002, 92, 1923–1932. [CrossRef]
44. *EZ-FRISK-7.26 A Program for Earthquake Ground Motion Estimation*; Risk Engineering Inc.: Boulder, CO, USA, 2008.
45. Boore, D.M.; Joyner, W.B.; Fumal, T.E. Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work. *Seismol. Res. Lett.* 1997, 68, 128–153. [CrossRef]
46. Abrahamson, N.; Silva, W. Summary of the Abrahamson & Silva NGA ground-motion relations. *Earthq. Spectra* 2008, 24, 67–97. [CrossRef]
47. Campbell, K.W.; Bozorgnia, Y. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s. *Earthq. Spectra* 2008, 24, 139–171. [CrossRef]
48. International Code Council. *IBC: International Building Code*; International Code Council: Washington, DC, USA, 2009; ISBN 978-1-58001-725-1.
49. International Conference of Building Officials. *Uniform Building Code, Volume 2: Structural Engineering Design Provisions*; ICBO: Whittier, CA, USA, 1997.
50. Pascucci, V.; Free, M.W.; Lubkowski, Z.A. Seismic Hazard and Seismic Design Requirements for the Arabian Peninsula Region. In *Proceedings of the 14th World Conference on Earthquake Engineering*, Beijing, China, 12–17 October 2008.
51. Avci, O.; Al Nouss, M. Seismic Assessment of Existing Lowrise and Midrise Reinforced Concrete Buildings Using the 2014 Qatar Construction Specification. J. Archit. Eng. 2018, 24, 04018028. [CrossRef]

52. Shahvar, M.P.; Zare, M.; Castellaro, S. A unified seismic catalog for the Iranian plateau (1900–2011). Seismol. Res. Lett. 2013, 84, 233–249. [CrossRef]

53. Deif, A.; Al-Şijbi, Y.; El-Hussain, I.; Ezzelarab, M.; Mohamed, A.M.E. Compiling an earthquake catalogue for the Arabian Plate, Western Asia. J. Asian Earth Sci. 2017, 147, 345–357. [CrossRef]

54. Ambraseys, N.N.; Melville, C.P. A History of Persian Earthquakes; Cambridge University Press: Cambridge, UK, 1982.

55. Ambraseys, N.N.; Melville, C.P.; Adams, R.D. The Seismicity of Egypt, Arabia and the Red Sea: A Historical Review; Cambridge University Press: New York, NY, USA, 1994.

56. International Seismological Centre On-Line Bulletin. Available online: https://doi.org/10.31905/D808B830 (accessed on 25 May 2019).

57. Di Giacomo, D.; Engdahl, E.R.; Storchak, D.A. The ISC-GEM Earthquake Catalogue (1904–2014): Status after the Extension Project. Earth Syst. Sci. Data 2018, 10, 1877–1899. [CrossRef]

58. Engdahl, E.R.; Van Der Hilst, R.; Buland, R. Global teleseismic earthquake relocation with improved travel times and procedures for depth determination. Bull. Seismol. Soc. Am. 1998, 88, 722–743.

59. Karimiparidari, S.; Zaré, M.; Memarian, H.; Kijko, A. Iranian earthquakes, a uniform catalog with moment magnitudes. J. Seismol. 2013, 17, 897–911. [CrossRef]

60. Şeşetyan, K.; Danciu, L.; Demircioğlu Tümsa, M.B.; Giardini, D.; Erdik, M.; Akkar, S.; Gülen, L.; Zare, M.; Admania, S.; Ansari, A.; et al. The 2014 seismic hazard model of the Middle East: Overview and results. Bull. Earthq. Eng. 2018, 16, 3535–3566. [CrossRef]

61. Danciu, L.; Şeşetyan, K.; Demircioğlu, M.; Gülen, L.; Zare, M.; Basili, R.; Elias, A.; Admania, S.; Tsereteli, N.; Yalçın, H.; et al. The 2014 Earthquake Model of the Middle East: Seismogenic sources. Bull. Earthq. Eng. 2018, 16, 3465–3496. [CrossRef]

62. NEIC-USGS. National Earthquake Information Center. Available online: http://neic.cr.usgs.gov/ (accessed on 25 May 2019).

63. Gardner, J.K.; Knopff, L. Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? Bull. Seismol. Soc. Am. 1974, 64, 1363–1367.

64. Sawires, R.; Peláez, J.A.; Ibrahim, H.A.; Fat-Helbary, R.E.; Henares, J.; Hamdache, M. Delineation and characterization of a new seismic source model for seismic hazard studies in Egypt. Nat. Hazards 2016, 80, 1823–1844. [CrossRef]

65. El-Hussain, I; Al-Şijbi, Y.; Deif, A.; Mohamed, A.M.E.; Ezzelarab, M. Developing a search source model for the Arabian Plate. Arab. J. Geosci. 2018, 11, 1–435. [CrossRef]

66. Taghizadeh-Farahmand, F.; Afşari, N.; Sodoudi, F. Crustal Thickness of Iran Inferred from Converted Waves. Pure Appl. Geophys. 2015, 172, 309–331. [CrossRef]

67. Afşari, N.; Sodoudi, F.; Taghizadeh Farahmand, F.; Ghassemi, M.R. Crustal structure of Northwest Zagros (Kermanshah) and Central Iran (Yazd and Isfahan) using teleseismic Ps converted phases. J. Seismol. 2011, 15, 341–353. [CrossRef]

68. Frankel, A. Mapping seismic hazard in the central and eastern United States. Seismol. Res. Lett. 1995, 66, 8–21. [CrossRef]

69. Peláez, J.A.; López Casado, C. Seismic hazard estimate at the Iberian Peninsula. Pure Appl. Geophys. 2002, 159, 2699–2713. [CrossRef]

70. Peláez, J.A.; Hamdache, M.; Casado, C.L. Seismic hazard in Northern Algeria using spatially smoothed seismicity. Results for peak ground acceleration. Tectonophysics 2003, 372, 105–119. [CrossRef]

71. Peláez, J.A.; Delgado, J.; López Casado, C. A preliminary probabilistic seismic hazard assessment in terms of Arias intensity in southeastern Spain. Eng. Geol. 2005, 77, 139–151. [CrossRef]

72. Chen, Y.-S.; Weatherill, G.; Pagani, M.; Cotton, F. A transparent and data-driven global tectonic regionalization model for seismic hazard assessment. Geophys. J. Int. 2018, 213, 1263–1280. [CrossRef]

73. Farhadi, A.; Farajpour, Z.; Pezeshk, S. Assessing predictive capability of ground-motion models for probabilistic seismic hazard in Iran. Bull. Seismol. Soc. Am. 2019, 109, 2073–2087. [CrossRef]

74. Boore, D.M.; Stewart, J.P.; Seyhan, E.; Atkinson, G.M. NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes. Earthq. Spectra 2014, 30, 1057–1085. [CrossRef]
75. Abrahamson, N.A.; Silva, W.J.; Kamai, R. Summary of the ASK14 ground motion relation for active crustal regions. *Earthq. Spectra* 2014, *30*, 1025–1055. [CrossRef]

76. Chiu, B.S.-J.; Youngs, R.R. Update of the Chiu and Youngs NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra. *Earthq. Spectra* 2014, *30*, 1117–1153. [CrossRef]

77. Campbell, K.W.; Bozorgnia, Y. NGA-West2 Ground Motion Model for the Average Horizontal Components of PGA, PGV, and 5% Damped Linear Acceleration Response Spectra. *Earthq. Spectra* 2014, *30*, 1087–1115. [CrossRef]

78. Ghasemi, H.; Zare, M.; Fukushima, Y.; Koketsu, K. An empirical spectral ground-motion model for Iran. *J. Seismol.* 2009, *13*, 499–515. [CrossRef]

79. Sedaghati, F.; Pezeshk, S. Partially nonergodic empirical ground-motion models for predicting horizontal and vertical PGA, PGV, and 5% damped linear acceleration response spectra using data from the Iranian plateau. *Bull. Seismol. Soc. Am.* 2017, *107*, 934–948. [CrossRef]

80. Shahidzadeh, M.S.; Yazdani, A. A Bayesian Updating Applied to Earthquake Ground-Motion Prediction Equations for Iran. *J. Earthq. Eng.* 2017, *21*, 290–324. [CrossRef]

81. Zafarani, H.; Luzi, L.; Lanzano, G.; Soghrat, M.R. Empirical equations for the prediction of PGA and pseudo spectral accelerations using Iranian strong-motion data. *J. Seismol.* 2018, *22*, 263–285. [CrossRef]

82. Farajpour, Z.; Pezeshk, S.; Zare, M. A new empirical ground-motion model for Iran. *Bull. Seismol. Soc. Am.* 2019, *109*, 732–744. [CrossRef]

83. Akkar, S.; Cagnan, Z. A Local Ground-Motion Predictive Model for Turkey, and Its Comparison with Other Regional and Global Ground-Motion Models. *Bull. Seismol. Soc. Am.* 2010, *100*, 2978–2995. [CrossRef]

84. Kalkan, E.; Guıllan, P. Site-Dependent Spectra Derived from Ground Motion Records in Turkey. *Earthq. Spectra* 2004, *20*, 1111–1138. [CrossRef]

85. Kanno, T.; Narita, A.; Morikawa, N.; Fujitoha, H.; Fukushima, Y. A New Attenuation Relation for Strong Ground Motion in Japan Based on Recorded Data. *Bull. Seismol. Soc. Am.* 2006, *96*, 879–897. [CrossRef]

86. Akkar, S.; Sandrikaya, M.A.; Bommer, J.J. Empirical ground-motion models for point- and extended-source crustal earthquake scenarios in Europe and the Middle East. *Bull. Earthq. Eng.* 2014, *12*, 359–387. [CrossRef]

87. Bindi, D.; Massa, M.; Luzi, L.; Ameri, G.; Pacor, F.; Puglia, R.; Augliera, P. Pan-European ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods up to 3.0 s using the RESORCE dataset. *Bull. Earthq. Eng.* 2014, *12*, 391–430. [CrossRef]

88. Kotha, S.R.; Bindi, D.; Cotton, F. Partially non-ergodic region specific GMPE for Europe and Middle-East. *Bull. Earthq. Eng.* 2016, *14*, 1245–1263. [CrossRef]

89. European Committee for Standardization. EC-8, (Eurocode 8) Design of Structures for Earthquake Resistance. Part 1: General Rules, Seismic Actions and Rules for Buildings; EN-1998-1; CEN: Brussels, Belgium, 2003.

90. Ancheta, T.D.; Darragh, R.B.; Stewart, J.P.; Seyhan, E.; Silva, W.J.; Chiu, B.S.J.; Wooddell, K.E.; Graves, R.; Kottke, A.R.; Boore, D.M.; et al. PEER NGA-West2 Database; Pacific Earthquake Engineering Research Center Report 2013/03; PEER: Berkeley, CA, USA, 2013.

91. Khan, M.M.; Kumar, G.K. Site-specific probabilistic seismic hazard assessment for proposed smart city, Warangal. *J. Earth Syst. Sci.* 2020, *129*, 147. [CrossRef]

92. Abdalzaher, M.S.; El-Hadjidi, M.; Gaber, H.; Badawy, A. Seismic hazard maps of Egypt based on spatially smoothed seismicity model and recent seismotectonic models. *J. African Earth Sci.* 2020, *170*, 103894. [CrossRef]

93. Du, W.; Pan, T.C. Probabilistic seismic hazard assessment for Singapore. *Nat. Hazards* 2020, *103*, 2883–2903. [CrossRef]

94. Ordaz, M.; Martinelli, F.; Aguilar, A.; Arboleda, J.; Meletti, C.; D’Amico, V. R-CRISIS. Program and Platform for Computing Seismic Hazard; UNAM Institute of Engineering: Mexico City, Mexico, 2017.

95. Wells, D.L.; Coppersmith, K.J. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bull. Seismol. Soc. Am.* 1994, *84*, 974–1002.

96. Deif, A.; El-Hussain, I.; Alshibji, Y.; Mohamed, A.M.E.S. Updating a probabilistic seismic hazard model for Sultanate of Oman. *Arab. J. Geosci.* 2020, *13*. [CrossRef]

97. Sawires, R.; Pelaez, J.A.; Fat-Helbary, R.E.; Ibrahim, H.A. Updated Probabilistic Seismic-Hazard Values for Egypt. *Bull. Seismol. Soc. Am.* 2016, *106*, 1788–1801. [CrossRef]

98. Kolathayar, S.; Sitharam, T.G. Comprehensive Probabilistic Seismic Hazard Analysis of the Andaman-Nicobar Regions. *Bull. Seismol. Soc. Am.* 2012, *102*, 2063–2076. [CrossRef]
99. Sokolov, V.; Zahran, H.M.; Youssef, S.E.-H.; El-Hadidy, M.; Alraddadi, W.W. Probabilistic seismic hazard assessment for Saudi Arabia using spatially smoothed seismicity and analysis of hazard uncertainty. *Bull. Earthq. Eng.* **2017**, *15*, 2695–2735. [CrossRef]

100. Sawires, R.; Peláez, J.A.; Fat-Helbary, R.E.; Panzera, F.; Ibrahim, H.A.; Hamdache, M. Probabilistic Seismic Hazard Deaggregation for Selected Egyptian Cities. *Pure Appl. Geophys.* **2017**, *174*, 1581–1600. [CrossRef]

101. Cornell, C.A. Engineering seismic risk analysis. *Bull. Seismol. Soc. Am.* **1986**, *58*, 1583–1606.

102. Field, E.H.; Jordan, T.H.; Cornell, C.A. OpenSHA: A developing community-modeling environment for seismic hazard analysis. *Seismol. Res. Lett.* **2003**, *74*, 406–419. [CrossRef]

103. Pagani, M.; Monelli, D.; Weatherill, G.; Danciu, L.; Silva, V.; Henshaw, P.; Butler, L.; Nastasi, M.; Panzeri, L.; et al. Openquake engine: An open hazard (and risk) software for the global earthquake model. *Seismol. Res. Lett.* **2014**, *85*, 692–702. [CrossRef]

104. Assatourians, K.; Atkinson, G.M. EqHaz: An open-source probabilistic seismic-hazard code based on the Monte Carlo simulation approach. *Seismol. Res. Lett.* **2013**, *84*, 516–524. [CrossRef]

105. McCann, M.W.; Reed, J.W. Lower bound earthquake magnitude for probabilistic seismic hazard evaluation. *Nucl. Eng. Des.* **1990**, *123*, 143–153. [CrossRef]

106. Malhotra, P.K. Return period of design ground motions. *Seismol. Res. Lett.* **2005**, *76*, 693–699. [CrossRef]

107. Newmark, N.M.; Hall, W.J. *Earthquake Spectra and Design*; Earthquake Engineering Research Institute: Oakland, CA, USA, 1982.

108. Bazzurro, P.; Cornell, C.A. Disaggregation of seismic hazard. *Bull. Seismol. Soc. Am.* **1999**, *89*, 501–520.

109. Harmsen, S.; Perkins, D.M.; Frankel, A. Deaggregation of probabilistic ground motions in the central and eastern United States. *Bull. Seismol. Soc. Am.* **1999**, *89*, 1–13.

110. McGuire, R.K. Probabilistic seismic hazard analysis and design earthquakes: Closing the loop. *Bull. Seismol. Soc. Am.* **1995**, *85*, 1275–1284.

111. Bernreuter, D.L. *Determining the Controlling Earthquake from Probabilistic Hazards for the Proposed Appendix B*; Lawrence Livermore National Laboratory, Report UCRL-JC-111964, Livermore, EE.UU.; U.S. Nuclear Regulatory Commission: Washington, DC, USA, 1992.

112. Chapman, M.C. A probabilistic approach to ground-motion selection for engineering design. *Bull. Seismol. Soc. Am.* **1995**, *85*, 937–942.

113. Barani, S.; Spallarossa, D.; Bazzurro, P. Disaggregation of probabilistic ground-motion Hazard in Italy. *Bull. Seismol. Soc. Am.* **2009**, *99*, 2638–2661. [CrossRef]

114. Hamdache, M.; Peláez, J.A.; Talbi, A.; Mobarki, M.; Casado, C.I. Ground-motion hazard values for northern Algeria. *Pure Appl. Geophys.* **2012**, *169*, 711–723. [CrossRef]

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