ASSESSMENT OF SEISMIC HAZARD FOR JORDAN

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ABSTRACT: Previous probabilistic seismic hazard analysis (PSHA) studies conducted for Jordan were all based on the classical PSHA model, in which earthquake magnitudes are assumed to exhibit an exponential distribution. However, it is observed that the exponentially distributed magnitude models may underestimate the recurrence rate of large magnitude earthquakes on individual fault segments. In this study, up-to-date information available on the seismic source zones and faults are utilized for the assessment of seismic hazard in Jordan. The classical PSHA model is taken as the basic model. However, as an alternative to the exponential magnitude distribution, the characteristic earthquake model is also considered. The seismic hazard model presented in this study is applied to assess the seismic hazard at different cities in Jordan, and the results are compared with those of the previous studies. Seismic hazard maps in terms of peak ground acceleration and spectral acceleration for a return period of 475 years are also presented.

INTRODUCTION

Most parts of Jordan, especially the regions along the Dead Sea-Jordan rift valley, are subject to significant seismic threat. Since the major cities and industry are located in earthquake prone regions, it is quite important to quantify the future seismic hazard in these regions and design and construct the engineering structures consistent with the resulting seismic hazard.

Considering the randomness in the occurrence of earthquakes with respect to time, space and magnitude as well as the various sources of uncertainties, probabilistic concepts and statistical methods are the appropriate tools for the assessment of seismic hazard at a specific site and also for the development of seismic hazard maps. The earlier probabilistic seismic hazard studies in the region dates back to the development of seismic hazard maps for Palestine. Later, a number of researchers have conducted studies for the prediction of seismic hazard in Jordan. Yüçemen has conducted a very comprehensive study for the assessment of the seismic hazard in Jordan and its vicinity by using probabilistic and statistical methods. The results were presented in the form of seismic hazard maps displaying iso-acceleration and iso-intensity contours corresponding to different return periods. In that study, the major problems were the identification of seismic source zones, delineation of faults, assessment of the fault parameters and also derivation of attenuation relationships based on local data.

In a later study conducted by Yüçemen, the problems associated with the location of seismic source zones were addressed in full and a model was described to quantify and incorporate explicitly the errors made in the demarcation of the source zone boundaries. The basic concept
introduced in that model was the assumption of random source zone boundaries instead of deterministic ones. To demonstrate the application of the proposed model, seismic hazard was computed at three different cities in Jordan. The sensitivity of results to the location uncertainty was examined and a comparison against the previous results was also made.

In the last decade a number of studies \cite{11, 12, 13, 14, 15} were conducted for the development of seismic hazard maps for Jordan and its vicinity. The probabilistic methodology and the computational algorithms were not different than the ones utilized by Yüçemen \cite{9, 10}, however these studies enjoyed the benefit of having more information and expert opinion for the delineation of seismic sources. Accordingly, more reliable seismic source models and seismicity parameters were used in these studies.

The main aim of this study is to conduct a PSHA for Jordan by using up-to-date information available on the seismic source zones and faults, but utilizing alternative probabilistic models and algorithms. Although the classical PSHA model is taken as the basic model, as an alternative to the exponential magnitude distribution, the characteristic earthquake model \cite{1, 2} is also considered. The seismic hazard model presented in this study is applied to assess the seismic hazard at different cities in Jordan and to develop seismic hazard maps in terms of peak ground acceleration (PGA) and spectral acceleration (SA) for a return period of 475 years.

**PROBABILISTIC SEISMIC HAZARD ANALYSIS MODELS**

In this section, firstly the classical PSHA model utilized in the previous studies conducted for Jordan is presented and then the model adopted in this study is briefly described.

**PSHA Model Utilized in the Previous Studies**

The probabilistic formulation used in the previous studies \cite{3-15} stems from the “classical” seismic hazard analysis model \cite{16}, which is based on the following general assumptions:

(i) The probability distribution of earthquake magnitudes is described by an exponential distribution which is derived based on a doubly-truncated linear recurrence relationship, with a lower bound, \( m_0 \) and an upper bound, \( m_1 \). The parameter describing the slope of this relationship is denoted by \( \beta \).

(ii) The earthquake occurrences are assumed to be independent events in time following a homogeneous Poisson process with a mean rate of occurrence, \( \nu \).

(iii) Peak horizontal ground acceleration (PGA), intensity (I) or spectral acceleration (SA) is taken as the earthquake severity parameter and the attenuation relationship expressing the selected parameter in terms of magnitude and a prescribed distance from site to source is utilized.

(iv) The spatial distribution of earthquakes is taken into consideration by associating them with seismic sources, which are generally modeled either as lines or areas.

For the computations, the majority of these studies used either FRISK \cite{17} or SEISRISK-III \cite{18}.

In the classical PSHA model, only the uncertainty in the attenuation equation is explicitly taken into consideration through a random correction factor and the uncertainty in the location of seismic sources is ignored. Among the previous studies, only in Yüçemen \cite{10} and Jiménez \cite{15} the uncertainty in the location of earthquake source coordinates is taken into consideration and its consequences are evaluated for hazard analysis.

**PSHA Model Utilized in This Study**

In this study the same assumptions were made and the same sources of uncertainties are taken into consideration as described above, except the distribution of earthquake magnitudes. As mentioned
before, in the classical PSHA, earthquake magnitudes are assumed to be exponentially distributed. Certain discrepancies observed between earthquake recurrence estimates based on past earthquake records and those based on seismological and geological investigations for specific regions, especially for active faults, have motivated investigators to develop alternative recurrence models to account for this discrepancy. The characteristic earthquake model is generally proposed as an alternative to the exponential magnitude distribution. Since the majority of seismic sources in Jordan are well-defined faults, it is quite desirable to apply the characteristic earthquake model and compare the results obtained from the exponentially distributed magnitudes. In the following, the magnitude recurrence relationships used in this study are explained.

Magnitude recurrence relationships: Recurrence relationships describe the relative frequency of different earthquake magnitudes which lead to the probability distribution of magnitudes. In most of the cases, seismic hazard analysis is based on the exponential probability distribution. Exponential probability density function for magnitudes, \( f_M(m) \), is derived from the linear magnitude-recurrence relationship and is given as follows:

\[
f_M(m) = \begin{cases} 
  k\beta e^{-\beta(m-m_0)} & m_0 \leq m \leq m_1 \\
  0 & \text{otherwise}
\end{cases}
\]  

\( k = \left[ 1 - e^{-\beta(m_1-m_0)} \right]^{-1} \)  

where, \( k \) is the normalizing constant, which adjusts the value of the cumulative distribution function to unity at \( m = m_1 \).

The characteristic earthquake model, which was proposed by Schwartz and Coppersmith \(^1\), has become a widely accepted model. They have indicated that the exponentially distributed magnitude model represents the distribution of earthquake magnitudes quite well in a large region, but may underestimate the recurrence rate of large earthquakes on individual fault segments. Later, Youngs and Coppersmith \(^2\) have derived a density function for magnitudes corresponding to the characteristic earthquake model. In this model magnitudes are assumed to be exponentially distributed up to the magnitude level \( m' \). Above this magnitude, the characteristic earthquake lies with a uniform distribution between \( (m_1-\Delta m_C) \) and \( m_1 \). Characteristic earthquake model proposed by Youngs and Coppersmith \(^2\) is illustrated in Figure 1.

In order to apply this model in their analysis, Youngs and Coppersmith \(^2\) made some simplifying assumptions. They assumed \( \Delta m_C \) to be equal to 0.5 magnitude unit, \( m' = m_1-\Delta m_C \) and frequency of the characteristic part of the distribution equals to the frequency of the exponential part at \( m' \approx 1.0 \). Applying these assumptions and normalizing the probability density function so that the total area under it equals unity, the probability density function of magnitude for the characteristic earthquake model takes the following form:

\[
f_M(m) = \begin{cases} 
  k\beta e^{-\beta(m-m_0)} & m_0 \leq m \leq m_1 - 0.5 \\
  k\beta e^{-\beta \left( m - \frac{3}{2} \Delta m_C \right)} & m_1 - 0.5 \leq m \leq m_1
\end{cases}
\]  

where, \( k \) is again the normalizing constant and is expressed as follows:

\[
k = \left[ 1 - e^{-\beta \left( m_1 - \frac{3}{2} \Delta m_C \right)} \right]^{-1}
\]  

\( \beta = \frac{1}{\Delta m_C} \) and \( \Delta m_C = 0.5 \).
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Seismic Data Base and Seismic Sources

For the location of seismic sources and the assessment of the values of the related seismicity parameters, mainly the information given in the report by Jiménez is used, since this study appears to be the most comprehensive one and has compiled up-to-date information. However, a certain degree of cross checking has also been done by using some of the other references.

The locations of the 16 seismic sources considered in this study are shown in Figure 2. For each seismic source, the estimates of the upper bound magnitude ($m_u$), the mean occurrence rate per year ($\nu$) and slope of the magnitude-frequency relationship ($\beta$), are given in Table 1. The lower bound magnitude ($m_0$) is taken as 4.0 for all sources. The seismic activity that cannot be associated with any one of these 16 seismic sources is treated as the background seismicity and its effect is smeared over the whole region. The values of the seismicity parameters corresponding to background seismicity are also shown in the last row of Table 1.

Peak ground acceleration (PGA) and spectral acceleration (SA) at T=0.2 s are selected as the basic parameters for the seismic hazard evaluation. The attenuation equations proposed by Ambraseys, et al., which are shown below, are used.

\[
\log \text{PGA} = -1.48 + 0.266 M_S - 0.922 \log \left[ (d^2 + 3.5^2)^{0.5} \right] \\
\log \text{SA(0.2 s)} = -0.84 + 0.219 M_S - 0.954 \log \left[ (d^2 + 4.2^2)^{0.5} \right]
\]

where, PGA: peak ground acceleration, SA(0.2 s): spectral acceleration for 0.2 s period, both values are in g units and for rock sites ($V_S=750$ m/s); $M_S$: surface magnitude and $d$ is the shortest distance to the surface projection of the fault rupture in km. The uncertainties associated with these attenuation equations are quantified by the respective standard deviations, which are taken as 0.25 for Log (PGA) and 0.27 for Log (SA at 0.2 s), as given in Ambraseys, et al. The uncertainty in the seismic source zone boundary location is not taken into consideration.
Table 1. “Best” estimates of seismic source parameters \(^{15}\)

| Source No. | Name of source                  | Type of source | \(m_1\) | \(v\) (per year) | \(|\beta|\) |
|------------|--------------------------------|----------------|--------|-----------------|--------|
| 1          | Dead Sea-Jordan River          | Line           | 7.5    | 0.33            | 1.73   |
| 2          | Wadi-Araba                     | Line           | 6.6    | 0.11            | 1.89   |
| 3          | Northern Faults                | Line           | 8.0    | 1.59            | 2.13   |
| 4          | Gulf of Aqaba                  | Line           | 6.5    | 1.51            | 1.96   |
| 5          | Gulf of Suez                   | Line           | 7.0    | 0.73            | 2.30   |
| 6          | Sirhan Faults                  | Line           | 7.0    | 0.05            | 1.63   |
| 7          | Farah Haifa                    | Line           | 5.8    | 0.09            | 1.98   |
| 8          | Wadi Karak                     | Line           | 4.7    | 0.023           | 1.01   |
| 9          | SE Maan                        | Line           | 4.6    | 0.029           | 0.67   |
| 10         | East Gulf of Aqaba             | Line           | 5.9    | 0.054           | 0.92   |
| 11         | Central Sinai                  | Line           | 4.0    | 0.01            | 0.69   |
| 12         | North East Gaza                | Line           | 4.5    | 0.022           | 0.78   |
| 13         | SE-Mediterranean 1             | Area           | 5.8    | 1.75            | 1.84   |
| 14         | SE-Mediterranean 2             | Area           | 5.8    | 0.49            | 2.42   |
| 15         | SE-Mediterranean 3             | Area           | 7.5    | 0.09            | 2.12   |
| 16         | Cyprus                         | Area           | 8.0    | 2.74            | 2.26   |
|            | Background                     | Area           | 5.0    | 0.15            | 1.75   |

**Computation of Seismic Hazard**

Two different software packages, namely EZ-FRISK \(^{20}\) and CRISIS2003 \(^{21}\) are used to carry out the seismic hazard computations according to the models described above. The values of the seismicity
parameters listed in Table 1 are used as the input to these computer programs. Eqs. (5) and (6) are taken as the ground motion estimation equations. To check the sensitivity of results to the magnitude recurrence relationship (purely exponential or exponential + characteristic), the type of seismic sources (line or area) and the computer program used (EZ-FRISK or CRISIS2003), the following four cases are considered.

**Case 1:** EZ-FRISK software is used by assuming exponential magnitude distribution for all of the 16 seismic sources and by taking the source types according to Table 1.

**Case 2:** EZ-FRISK software is used by assuming exponential magnitude distribution for all area sources and the characteristic earthquake model for all line sources (faults) with $m_1 \geq 6$, considering the source types given in Table 1.

**Case 3:** CRISIS2003 software is used by assuming exponential magnitude distribution for all of the 16 seismic sources and taking the source types according to Table 1.

**Case 4:** CRISIS2003 software is used by assuming exponential magnitude distribution for all of the 16 seismic sources and modeling line sources also as area sources, as described in Jiménez[15].

Seismic hazard computations are carried out for each one of these four cases and PGA and SA(0.2 s) values corresponding to return periods of 475, 1000 and 2475 years are presented in Table 2 for Azraq, Amman, Irbid and Aqaba. These return periods correspond, respectively, to 10%, 5% and 2% probabilities of exceedance in 50 years. Among the cases described above, Case 2 represents our best estimate, since the assumptions listed in Case 2 appear to be more consistent with the seismicity of Jordan.

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>City</td>
<td>PGA</td>
<td>SA(0.2 s)</td>
<td>PGA</td>
</tr>
<tr>
<td></td>
<td>475</td>
<td>1000</td>
<td>2475</td>
</tr>
<tr>
<td>Azraq</td>
<td>0.05</td>
<td>0.07</td>
<td>0.08</td>
</tr>
<tr>
<td>Amman</td>
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<td>0.13</td>
<td>0.17</td>
</tr>
<tr>
<td>Irbid</td>
<td>0.12</td>
<td>0.16</td>
<td>0.21</td>
</tr>
<tr>
<td>Aqaba</td>
<td>0.29</td>
<td>0.36</td>
<td>0.47</td>
</tr>
</tbody>
</table>

The contributions of the different seismic sources to the seismic hazard at these cities are analyzed according to the assumptions listed in Case 2. Because of space limitation only the results for Amman are displayed here. The seismic hazard resulting in Amman due to the highest contributing five seismic sources, namely: Dead Sea-Jordan River, Farah Haifa, Gulf of Aqaba,
Northern Faults and Sirhan Faults are shown in Figure 3 in the form of seismic hazard curves. As expected the main contribution comes from the Dead Sea-Jordan River seismic source and this fault completely dominates the seismic hazard for Amman for PGA values greater than 0.1 g.

Seismic hazard maps are developed according to the assumptions listed in Case 3. The resulting maps, in terms of PGA and SA at 0.2 s, corresponding to a return period of 475 years (10% probability of exceedance in 50 years) are shown in Figures 4 and 5. A grid size of 0.2˚ x 0.2˚ is used in producing these maps. The selection of Case 3 instead of Case 2, is due to the fact that seismic hazard mapping is possible within the software CRISIS2003, whereas EZ-FRISK requires an additional program for the plotting of the iso-acceleration contours.

**DISCUSSION OF RESULTS AND CONCLUSIONS**

In this study, seismic hazard in Jordan is quantified based on up-to-date information on the seismic sources. The results are presented in the form of seismic hazard maps. Also the PGA and SA(0.2 s) values are computed for Azraq, Amman, Irbid and Aqaba for different return periods and under different assumptions. The main conclusions and the discussion of results are as follows:

(i) Cases 1 and 3 are based on the same input data and the same seismic hazard model, but the computer programs used for carrying out the numerical computations are different. In Case 1, EZ-FRISK and in Case 3, CRISIS2003 programs are used. Since the results shown in Table 2 for these two cases are quite close to each other, both computer programs can be rated as equally “good”. It is observed that for Azraq, Amman and Irbid, EZ-FRISK gives slightly higher results, whereas for Aqaba the opposite trend is valid.
Figure 4. Seismic hazard map for Jordan in terms of PGA corresponding to a return period of 475 years (10% probability of exceedance in 50 years)

Figure 5. Seismic hazard map for Jordan in terms of SA(0.2 s) corresponding to a return period of 475 years (10% probability of exceedance in 50 years)
(ii) For the same hazard level, Case 2, which is based on our best estimate alternative set, gives consistently the highest PGA and SA values compared to the other three cases. This is due to the use of the characteristic earthquake model for major faults. Since the recurrence rates of the characteristic earthquakes for the faults listed in Table 1 were not available, the “generalized” characteristic earthquake model of Youngs and Coppersmith \(^2\) is adopted. More reliable seismic hazard values will be obtained if the recurrence rates of the characteristic earthquakes are based on slip rates and observed recurrence intervals of large magnitude earthquakes.

(iii) Comparison of Cases 1 and 2 shows that the characteristic earthquake model gives PGA and SA values 1.4 to 1.6 times more than those obtained based on the assumption that earthquake magnitudes are exponentially distributed. This significant difference indicates the importance of the use of the appropriate recurrence model for faults.

(iv) Examination of Figure 3 reveals that the most important source of seismic threat to Amman is the Dead Sea-Jordan River fault. Especially, for seismic hazard associated with PGA values exceeding 0.1 g, almost the entire seismic hazard comes from this seismic source. Therefore, special attention should be paid to the reliable assessment of the seismicity parameters of the Dead Sea-Jordan River fault in future seismological studies.

(v) In this study the uncertainty associated with the description of the geographical coordinates of source zone boundaries is ignored. SEISRISK-III \(^18\) software enables such an uncertainty to be included into the analysis by modeling the faults as area sources with a narrow width. The introduction of the source zone boundary uncertainty causes the seismicity concentrated around a fault to be dispersed over a wider region proportional to the standard deviation modeling this uncertainty. This causes a decrease in the intensity of seismic hazard in the neighborhood of the fault, since the seismicity is distributed over a larger area. Therefore, for faults it is not realistic to incorporate this uncertainty, whereas for area sources it could be appropriate. Besides, based on a study conducted for Jordan, Yücemen \(^10\) concluded that for sites under the threat of a number of seismic sources of either type (i.e. area or line), the incorporation of source location uncertainty influences the hazard estimate to a relatively smaller extent compared to other factors of uncertainty, such as the uncertainty involved in the attenuation model.

(vi) The results obtained in this study are generally in agreement with those reported in the previous studies. However, in view of the significantly higher results obtained from the characteristic earthquake model, we recommend the use of the characteristic earthquake model for faults together with the exponential distribution for smaller earthquakes and area sources. Furthermore, the Poisson model can be replaced by the renewal models to take into consideration the time dependence of earthquake occurrences, if data on the recurrence intervals can be obtained.

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