Assessment of Earthquake Hazard Parameters with Bayesian Approach Method Around Karliova Triple Junction, Eastern Turkey

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Abstract. In this study, the Bayesian Approach method is used to evaluate earthquake hazard parameters of maximum regional magnitude (Mmax), β value, and seismic activity rate or intensity (λ) and their uncertainties for next 5, 10, 25, 50, 100 years around Karlıova Triple Junction (KTJ). A compiled earthquake catalog that is homogenous for Ms ≥ 3.0 was completed during the period from 1900 to 2017. We are divided into four different seismic source regions based on epicenter distribution, tectonic, seismicity, faults around KTJ. We two historical earthquakes (1866, Ms=7.2 for Region 3 (Between Bingöl-Karlıova-Muş-Bitlis (Bahçeköy Fault Zone-Üzunpınar Fault- Karakoçan Fault- Muş Fault Zones –Kavakbaşı Fault)) and 1874, Ms=7.1 for Region 4 (Between Malatya-Elazığ-Tunceli (Palu Basin- Pütürge Basin-Erkenek Fault-Malatya Fault)) are included around KTJ. The computed Mmax values are between 7.71 and 8.17. The quantiles of functions of distributions of true and apparent magnitude on a given time interval [0, T] are evaluated. The quantiles of functions of distributions of apparent and true magnitudes for next time intervals of 5, 10, 25, 50, and 100 years are calculated for confidence limits of probability levels of 50, 70, and 90 % around KTJ. According to the computed earthquake hazard parameters, Erzincan Basin-Ovacık Fault-Pülümür Fault-Yedisu Basin region was the most seismic active regions of KTJ. Erzincan Basin-Ovacık Fault-Pülümür Fault-Yedisu Basin region is estimated the highest earthquake magnitude 7.16 with a 90 % probability level in the next 100 years which the most dangerous region compared to other regions. The results of this study can be used in earthquake hazard studies of the East Anatolian region.

1. Introduction

Even though the East Anatolian Fault System (EAFS) is seismically less active than the North Anatolian Fault System (NAFS), historical proof propose that it is, nonetheless, talented of producing earthquakes with magnitudes up to $M_w = 7.0$.

The East Anatolian Fault Zone is a 550 km-long, approximately northeast-trending, left lateral strike-slip fault zone that takes up the relative motion between the Anatolian and the Eurasian plates and, between the Arabian and African plates. It extended from Karlıova triple junction in the northeast to the Maras triple junction in the southwest were it intersects the Dead Sea Fault.

The North Anatolian Fault (NAF) is the most eminent tectonic feature of the region. It was one of the best known strike slip faults about 1500 km long, seismically active right lateral strike-slip fault system extending from the Karlıova triple junction in eastern Turkey to mainland Greece in the world.

The Karlıova region is the location of the triple junction between the North Anatolian Fault Zone and East Anatolian Fault Zone and Varto Fault Zone with the boundaries of the Eurasian Plate, Anatolian
Plate and the Arabian Plate. It was the Mus fold and thrust belt, which passes to the east into the Zagros fold and thrust belt.

The Karlıova earthquake occurred at magnitude M=6.7 near Karlıova in Bingöl, on 17 August history in the Eastern Anatolia Region of Turkey.

The aim of this study, the Bayesian Approach method used to evaluate earthquake hazard parameters (maximum regional magnitude ($M_{\text{max}}$), β value, and seismic activity rate or intensity ($\lambda$) and their uncertainties) for next 5, 10, 25, 50, 100 years around Karlıova Triple Junction (KTJ), Eastern Turkey. A homogenous earthquake catalog used for $M_s \geq 3.0$ for a time period between 1900 and 2017. We are divided into 4 different seismogenic source regions based on tectonic structure, geology, epicenter distribution e.g. (Figure 1).

Two earthquakes were observed around the KTJ in the historical period and it wasn’t observed large earthquake for the instrumental period. That’s why, historical earthquakes (1866, $M_s=7.2$ for Region 3 (Between Bingöl-Karlıova-Muş-Butlis (Bahçeköy Fault Zone-Uzunpinar Fault Zone- Karakoçan Fault- Muş Fault Zones –Kavakbaşı Fault)) and 1874, $M_s=7.1$ for Region 4 (Between Malatya-Elazığ-Tunceli (Pulu Basin- Pütürge Basin-Erkenek Fault-Malatya Fault)) are included around KTJ.

2. Method
2.1- Bayesian Method

The theory of Bayesian probability expresses the formulation of the inferences from data straightforward and allows the solution of problems earthquakes occurrences.
Let $R$ be some value, which was measured or estimated as a sequence on a “past” time interval ($\tau, o$):

$$\vec{R}^{(n)} = (R_1, \ldots, R_n), \quad R_i \geq R_0, \quad R_n = \max((R_1, \ldots, R_n), \quad 1 \leq i \leq n \quad (1)$$

Where, $i = 1, 2, \ldots, n$; and $R_0$ is a minimum cutoff value of magnitudes ($M$), i.e., defined by possibilities of registration system, or it may be a minimum value from which the value written in Eq. (1) is statistically representative.

Two main assumptions for Eq. (1) were proposed. Our first assumption is that values of $\vec{R}^{(n)}$ follows by Eq. (1) of the Gutenberg–Richter law of distribution which is expressed:

$$\text{Prob} \{R < r\} = F\left(\frac{x}{R_0}, \rho, \beta\right) = \frac{e^{-\beta R_0} - e^{-\beta x}}{e^{-\beta R_0} - e^{-\beta \rho}}, \quad R_0 \leq x \leq \rho \quad (2)$$

While the second assumption is that the sequence of Eq. (1) is Poisson process with some activity rate or intensity $\lambda$ which is an unknown parameter. It is necessary to note that the distribution expressed by Eq. (2) is the Gutenberg-Richter law. If three unknown parameters ($\rho$, $\beta$ and $\lambda$) can be written, the full vector is:

$$\theta = (\rho, \beta, \lambda) \quad (3)$$

Where, from both Eq. (2) and Eq. (3), $\rho$ is the unknown parameter that represents the maximum possible value of $R$, for instance, ‘maximum regional magnitudes ($M$)” in a given seismogenic region. The unknown parameter $\beta$ is usually called the ‘slope’ of the Gutenberg–Richter law, while the intensity or rate value $\lambda$ is also an unknown parameter.

Let $n(x|\delta)$ be the probabilistic density of error $\varepsilon$, where $\delta$ is some scale parameter of the density and epsilon ($\varepsilon$) value is the error between the true magnitude ($R$) and the apparent magnitude ($\vec{R}$). We can estimate values of true magnitude taking into account different hypotheses about the probability distribution of epsilon (for example, uniform) and about parameters of this distribution. We shall use below the uniform distribution density:

$$n(x|\delta) = \begin{cases} \frac{1}{2\delta}, & |x| \leq \delta \\ 0, & |x| > \delta \end{cases} \quad (4)$$

Where $\Pi$ be a priori uncertainty domain of values of parameters $\theta$:

$$\Pi = \{\lambda_{\min} < \lambda \leq \lambda_{\max}, \beta_{\min} \leq \beta \leq \beta_{\max}, \rho_{\min} \leq \rho \leq \rho_{\max}\} \quad (5)$$

We shall consider the a priori density of the vector $\theta$ to be uniform in the domain $\Pi$.

The Bayesian method used in the present method is based on Bayes formula (Rao 1965).

$$F\theta|\vec{R}^{(n)} = \int f(R|V, \delta) dV \quad (6)$$

In order to use Eq. (6), we must have an expression for the function $f(R|\theta, \delta)$. The sequence in Eq. (1), with the assumption of a Poisson character and independent of its members, we can obtain:
\[ f(\vec{R}^{(n)}|\theta, \delta) = \prod f(R_i|\theta, \delta) \prod f(R_n|\theta, \delta) \prod \frac{\exp(-\lambda(\theta, \delta)\tau) \times (-1(\theta, \delta)\tau)^n}{n!} \]  

(7)

We can compute a Bayesian estimate of vector \( \theta \):

\[ \theta(\vec{R}^{(n)}|\delta) = \int Vf(V|\vec{R}, \delta)dV \]

(8)

One of the computations in (Eq. 8) contains an estimate of maximum value of \( \tau \). Using a formula analogous to Eq. (8), we must obtain Bayesian estimate for any of the functions. The most important are estimates of quantiles of distribution functions of true and apparent \( R \)-values on a given future time interval \([0,T]\), for instance for \( \alpha \) quantiles of apparent values:

\[ \tilde{Y}(\alpha|\vec{R}^{(n)}, \delta) = \int Vf(V|\vec{R}, \delta)* f(V|\vec{R}, \delta) dV \]

(9)

\[ \tilde{Y}_T(\delta|\vec{R}, \delta) \] for \( \alpha \) quantiles of true values is written analogously to Eq. (9). Using averaging over the density (Eq. 8, 9) we can also estimate variances of Bayesian estimates (Eq. 9, 10). For example:

\[ Var\left\{ \tilde{Y}_T(\alpha|\vec{R}^{(n)}, \delta) \right\} = \int \left( \tilde{Y}_T(\alpha|\vec{R}, \delta) - \tilde{Y}_T(\alpha|\vec{R}, \delta) \right)^2 * f(V|\vec{R}, \delta) dV \]

(10)

Firstly we will set \( \rho_{\min} = R_c - \delta \). As for the values of \( \rho_{\max} \), it is introduced by the user of the method and depends on the specifics of the data series (Eq. 1). Boundary values for the slope \( \beta \) are estimated by the formula:

\[ \beta_{\min} = (\beta_0 \cdot (1 - \gamma)), \quad \beta_{\max} = \beta_0 \cdot (1 + \gamma), \quad 0 < \gamma < 1 \]

(11)

Where \( \beta_0 \) is the “central” value and is obtained as the maximum likelihood estimate of the slope for the Gutenberg–Richter law:

\[ \sum_{i=1}^{n} \ln \left\{ \frac{\beta e^{-\beta R_i}}{e^{-\beta \rho_{\min} - e^{-\beta R_i}}} \right\} \rightarrow \text{Max} \; \beta, \beta \varepsilon(0, \beta_{\max}) \]

(12)

, where, \( \beta_0 \) is a rather large value.

For setting boundary values for rate or intensity (\( \lambda \)) in Eq. (5), we use the following reasons. As a consequence of normal approximation for a Poisson process for a rather large \( n \) (Cox and Lewis 1966), the standard deviation of the value \( \lambda \tau \) has the approximation value \( \sqrt{n} \approx \sqrt{\lambda \tau} \). So taking boundaries at \( \pm 3\sigma \), we will obtain:
\[ \lambda_{\text{min}} = \lambda_0 \left( 1 - \frac{3}{\sqrt{\lambda_0 \tau}} \right), \lambda_{\text{max}} = \lambda_0 \left( 1 + \frac{3}{\sqrt{\lambda_0 \tau}} \right) \]

\[ \lambda_0 = \frac{\lambda_0}{\gamma_f (\theta_0, \delta_1)} \quad \lambda_0 = \frac{n}{\tau} \quad (13) \]

3. Results and discussions

Probabilistic tools for earthquake hazard evaluation are demonstrated for the four different seismic source regions examined. The computed \( M_{\text{max}} \) values changed between 7.71 and 8.17.

While the highest magnitude value is calculated in the Region 1 related to Erzincan Basin-Ovacık Fault-Püümür Fault-Yedisu Basin (on the NAFZ), the lowest value is calculated in the Region 5 related to Karlıova Basin-Kandilli Fault-Erzurum Fault Zones-Varıto Fault Zones.

In addition to, the a posteriori probability density and the a posteriori probability distribution function estimated for both “apparent” and “true” \( M_{\text{max}(T)} \) values occurred in a future time interval of 5, 10, 25, 50 and 100 years. For example, Region 1 (Erzincan Basin-Ovacık Fault-Püümür Fault-Yedisu Basin) estimated the a posteriori probability density and the posteriori probability distribution function of “apparent” and “true” \( M_{\text{max}(T)} \) in next \( T \) years.

Quantiles that must considered as hazard estimation are the “tail” probabilities \( P(M_{\text{max}(T)}>M) \) for the apparent and the true magnitudes (Figure 4). Finally, The \( \alpha \)-posteriori \( M \)-quantiles are estimated for the four seismic source regions of “apparent” magnitude and “true” magnitude and for probabilities of 0.50, 0.70, 0.90 in next times \( T \) for 5, 10, 25, 50 and 100 years. The estimated quantiles for both “apparent” and “true” magnitudes \( M_{\text{max}(T)} \) are determined for 0.50, 0.70, 0.90 levels of probability and are tabulated (Table 2).

![Figure 2](image.png)

*Figure 2. The a posteriori probability density for the apparent and true \( M_{\text{max}(T)} \) magnitudes determined for region 1 that will occur in a next \( T=5, 10, 25, 50 \) and 100 years in KTJ*
Figure 3. The a posteriori probability distribution function determined for the apparent and true \( M_{\text{max}}(T) \) magnitudes for region 1 that will occur in a next \( T=5, 10, 25, 50 \) and 100 years.

Figure 4. The 'Tail' probabilities \( 1-\phi(M) = \text{Prob}(M_{\text{max}}(T) \geq M) \) for the apparent and true \( M_{\text{max}}(T) \) determined for region 1 that will occur in a next \( T=5, 10, 25, 50 \) and 100 years.

Table 1. The KTJ for 4 source regions estimated of the Bayesian analysis.

| Region | Region Name                                                                 | N   | \( M_{\text{max}} \pm \sigma_{M_{\text{max}}} \) | \( M_{\text{max}}^{\text{obs}} \pm \sigma_{M_{\text{max}}} \) | \( \beta \pm \sigma_{\beta} \) | \( \lambda \pm \sigma_{\lambda} \) |
|--------|------------------------------------------------------------------------------|-----|-------------------------------------------------|-------------------------------------------------|---------------------------------|---------------------------------|
| 1      | Erzincan Basin-Ovacık Fault-Püümürm Fault-Yedisu Basin                        | 554 | 8.17±0.19                                       | 7.9                                             | 1.99±0.84                       | 0.13±0.56                       |
| 2      | Karlıova Basin-Kandilli Fault-Erzurum Fault Zones-Varto Fault Zones           | 463 | 7.71±0.44                                       | 7.0                                             | 1.94±0.90                       | 0.11±0.52                       |
| 3      | Between Bingöl-Karlıova-Muş-Şitlis (Bahçeköy Fault Zone-Uzunpınar Fault Zone-Karakoçan Fault Zone-Muş Fault Zones-Kavakbaşı Fault) | 317 | 7.81±0.39                                       | 7.2                                             | 1.76±0.99                       | 0.56±0.31                       |
| 4      | Between Malatya-Elazığ-Tunceli (Pulu Basin-Pütürge Basin-Erkenek Fault-Malatya Fault) | 785 | 7.77±0.42                                       | 7.1                                             | 2.33±0.83                       | 0.14±0.51                       |
According to the computed earthquake hazard parameters, Erzincan Basin-Ovacık Fault-Pülümür Fault-Yedisu Basin region was the most seismic active regions of KTJ. Erzincan Basin-Ovacık Fault-Pülümür Fault-Yedisu Basin region is estimated the highest earthquake magnitude 7.16 with a 90 % probability level in the next 100 years which the most dangerous region compared to other regions. The results of this study can be used in earthquake hazard studies of the East Anatolian region.

Table 2. The KTJ for 4 source regions estimated the quantiles of the ‘apparent magnitudes’ $M_{\text{app}}(T)$ of the levels of probability $\alpha=0.50$, $\alpha=0.70$ and $\alpha=0.90$ in next years ($T=5, 10, 25, 50$ and $100$).

| Years   | Prob= 0.5 | M_app= | M_true= | Disp=   | Prob= 0.7 | M_app= | M_true= | Disp=   | Prob= 0.9 | M_app= | M_true= | Disp=   |
|---------|-----------|--------|---------|---------|-----------|--------|---------|---------|-----------|--------|---------|---------|
| 5-Year  |           |        |         |         |           |        |         |         |           |        |         |         |
|         | Prob= 0.5 | 4.80256 | 4.78932 | 0.07931 |           |        |         |         |           |        |         |         |
|         | Prob= 0.7 | 5.13532 | 5.12208 | 0.09277 |           |        |         |         |           |        |         |         |
|         | Prob= 0.9 | 5.74403 | 5.7308  | 0.1168  |           |        |         |         |           |        |         |         |
| 10-Year |           |        |         |         |           |        |         |         |           |        |         |         |
|         | Prob= 0.5 | 5.1497  | 5.13646 | 0.09335 |           |        |         |         |           |        |         |         |
|         | Prob= 0.7 | 5.4818  | 5.46856 | 0.10662 |           |        |         |         |           |        |         |         |
|         | Prob= 0.9 | 6.0734  | 6.0741  | 0.12932 |           |        |         |         |           |        |         |         |
| 25-Year |           |        |         |         |           |        |         |         |           |        |         |         |
|         | Prob= 0.5 | 5.93758 | 5.92434 | 0.12401 |           |        |         |         |           |        |         |         |
|         | Prob= 0.7 | 6.53388 | 6.52064 | 0.14284 |           |        |         |         |           |        |         |         |
|         | Prob= 0.9 | 6.9518  | 6.93856 | 0.12453 |           |        |         |         |           |        |         |         |
| 50-Year |           |        |         |         |           |        |         |         |           |        |         |         |
|         | Prob= 0.5 | 5.60742 | 5.59418 | 0.11154 |           |        |         |         |           |        |         |         |
|         | Prob= 0.7 | 5.93758 | 5.92434 | 0.12401 |           |        |         |         |           |        |         |         |
|         | Prob= 0.9 | 6.68658 | 6.64735 | 0.14894 |           |        |         |         |           |        |         |         |
| 100-Year|           |        |         |         |           |        |         |         |           |        |         |         |
|         | Prob= 0.5 | 6.29281 | 6.27957 | 0.13607 |           |        |         |         |           |        |         |         |
|         | Prob= 0.7 | 6.61369 | 6.60045 | 0.14471 |           |        |         |         |           |        |         |         |
|         | Prob= 0.9 | 7.16931 | 7.15608 | 0.14984 |           |        |         |         |           |        |         |         |

Table 3. The KTJ for 4 source regions estimated the quantiles of the ‘apparent magnitudes’ $M_{\text{app}}(T)$ of the levels of probability $\alpha=0.50$, $\alpha=0.70$ and $\alpha=0.90$ in next years ($T=5, 10, 25, 50$ and $100$).

| Years   | Prob= 0.5 | M_app= | M_true= | Disp=   | Prob= 0.7 | M_app= | M_true= | Disp=   | Prob= 0.9 | M_app= | M_true= | Disp=   |
|---------|-----------|--------|---------|---------|-----------|--------|---------|---------|-----------|--------|---------|---------|
| 5-Year  |           |        |         |         |           |        |         |         |           |        |         |         |
|         | Prob= 0.5 | 4.76486 | 4.75199 | 0.084906 |           |        |         |         |           |        |         |         |
|         | Prob= 0.7 | 5.01547 | 5.09259 | 0.099388 |           |        |         |         |           |        |         |         |
|         | Prob= 0.9 | 5.72343 | 5.71056 | 0.123712 |           |        |         |         |           |        |         |         |
| 10-Year |           |        |         |         |           |        |         |         |           |        |         |         |
|         | Prob= 0.5 | 5.12015 | 5.10728 | 0.100002 |           |        |         |         |           |        |         |         |
|         | Prob= 0.7 | 5.4584  | 5.44553 | 0.113727 |           |        |         |         |           |        |         |         |
|         | Prob= 0.9 | 6.06559 | 6.05271 | 0.135294 |           |        |         |         |           |        |         |         |
| 25-Year |           |        |         |         |           |        |         |         |           |        |         |         |
|         | Prob= 0.5 | 5.58566 | 5.57278 | 0.118623 |           |        |         |         |           |        |         |         |
|         | Prob= 0.7 | 5.91718 | 5.90431 | 0.130452 |           |        |         |         |           |        |         |         |
|         | Prob= 0.9 | 6.49593 | 6.48306 | 0.149304 |           |        |         |         |           |        |         |         |
| 50-Year |           |        |         |         |           |        |         |         |           |        |         |         |
|         | Prob= 0.5 | 5.93134 | 5.91847 | 0.130925 |           |        |         |         |           |        |         |         |
|         | Prob= 0.7 | 6.2527 | 6.23982 | 0.141158 |           |        |         |         |           |        |         |         |
|         | Prob= 0.9 | 6.79311 | 6.78023 | 0.164667 |           |        |         |         |           |        |         |         |
| 100-Year|           |        |         |         |           |        |         |         |           |        |         |         |
|         | Prob= 0.5 | 6.26628 | 6.2534  | 0.141583 |           |        |         |         |           |        |         |         |
|         | Prob= 0.7 | 6.57021 | 6.55733 | 0.152277 |           |        |         |         |           |        |         |         |
|         | Prob= 0.9 | 7.05387 | 7.04093 | 0.192669 |           |        |         |         |           |        |         |         |
| Years  | Prob| M_app| M_true| Disp   | M_app| M_true| Disp   |
|--------|-----|------|-------|--------|------|-------|--------|
| 5-Year | 0.5 | 4.28999 | 4.27511 | 0.072165 | 0.072899 |
|        | 0.7 | 4.58613 | 4.57125 | 0.087041 | 0.087789 |
|        | 0.9 | 5.12878 | 5.1139  | 0.114325 | 0.115085 |
| 10-Year| 0.5 | 4.59893 | 4.58405 | 0.087688 | 0.088436 |
|        | 0.7 | 4.89479 | 4.8799  | 0.102614 | 0.10337 |
|        | 0.9 | 5.43604 | 5.42116 | 0.129338 | 0.130101 |
| 25-Year| 0.5 | 5.00682 | 4.99194 | 0.108241 | 0.108998 |
|        | 0.7 | 5.30183 | 5.28694 | 0.122852 | 0.123614 |
|        | 0.9 | 5.83901 | 5.82413 | 0.147668 | 0.148433 |
| 50-Year| 0.5 | 5.31456 | 5.29968 | 0.123473 | 0.124235 |
|        | 0.7 | 5.60817 | 5.59328 | 0.137421 | 0.138186 |
|        | 0.9 | 6.13889 | 6.124   | 0.159476 | 0.16024 |
| 100-Year| 0.5 | 5.62082 | 5.60593 | 0.138003 | 0.138767 |
|        | 0.7 | 5.91172 | 5.89684 | 0.15071  | 0.151475 |
|        | 0.9 | 6.43052 | 6.41564 | 0.16885  | 0.169604 |

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