PROBABILISTIC PREDICTION OF THE NEXT EARTHQUAKE IN THE NAFZ (NORTH ANATOLIAN FAULT ZONE), TURKEY

KUZEY ANADOLU FAY ZONUNDA (NAFZ) GELECEK DEPREMLERİN OLASILIKSAL TAHMİNİ

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ABSTRACT
Statistical methods are useful for characterizing seismic hazard because earthquakes are, for all practical purposes, random phenomena. They provide additional insights to the seismic hazard or risk problem. Seismic risk and earthquake occurrence probabilities can be estimated by using probability distributions. In this study Weibull, Log-normal, Log-logistic, Exponential and Gamma distributions have been examined for which one has the best fit for the given data. Kolmogorov-Smirnov test statistics was used at the research of the distribution best represents earthquake data. At the end of the test, it has been detected that Weibull distribution is more appropriate than other distributions.

Key Words: Earthquake Prediction, Probability Distributions, Kolmogorov-Smirnov Test

ÖZET
Depremler rassal olaylar olduğu için bu alanda istatistiksel metotların kullanımı yaygındır. İstatistiksel metotlar risk problemlerinin çözümlenmesinde kullanılır. Sismik risk ve deprem meydana gelme olasılıkları istatistiksel olasılık dağılımları yardımıyla tahmin edilebilir. Bu çalışmada Weibull, Log-normal, Log-lojistik, Üstel ve Gamma dağılımları kullanılarak deprem verisini en iyi şekilde temsil edecek olasılık dağılımı bulunmaya çalışılmıştır. Bu amaçla etkin olasılık dağılımının belirlenmesinde Kolmogorov-Smirnov test istatistiği kullanılmıştır. Çalışma sonucunda Weibull dağılımının diğer olasılık dağılımlarına gore deprem verisini en iyi şekilde temsil ettiği görülmüştür.

Anahtar Kelimeler : *Deprem tahmini, Olasılık Dağılımları, Kolmogorov- Simirnov Testi*

1. Introduction
It has been one quarter century since Utsu (1972a, 1972b), Rikitake (1974) and Hagiwara (1974) proposed a probabilistic approach for forecasting the time of the next earthquake on a specific fault. Poisson distribution is applied for seismicty studies (for example, Cornell 1968; Caputo 1974; Shah 1975; Bath 1978; Cluff at al. 1980). A number candidate statistical distributions have been proposed for

computation of conditional probabilistic of future earthquakes, including the Double Exponential (Utsu, 1972b), Gaussian (Rikitake, 1974), Weibull (Hagiwara, 1974; Rikitake, 1974), Log-normal (Nishenko and Buland, 1987) and Gamma (Utsu, 1984), Pareto (Sergio G. Ferráes, 2003) distributions. The difficulty lies in determining the correct distribution, given data of large seismic event on a given faults. Nishenko and Buland (1987) obtained a reasonably good fit to a log-normal distribution. Mc Nolly and Minster (1981) have argued that a Weibull distribution is more appropriate. [Workshop on Earthquake Recurrence, 1999]. In this study, in order to find the probability distribution best represents the data set, we have compared Weibull, Log-normal, Log-logistic, Exponential and Gamma distributions through Kolmogorov-Smirnov test.

NAFZ (North Anatolian Fault Zone) were selected as an area of investigation. In this paper, the earthquake data which were occurred in the area coordinated 39.00^o – 42.00^o North latitudes and 30.00^0-40.00^0 East longitudes between 1900-2000 years and whose magnitudes equal 5 or higher were used (http://www.koeri.boun.edu.tr - Boğaziçi Univ. Kandilli Observatory and Earthquake Research Institute). The last earthquake occurred on the NAFZ is İzmit Eartquake of 19 August 1999. Kocaeli earthquake occurred at 00:01:39 UTC (3:01 a.m. local time), and was centered at 40.74 N., 29.86 E., which places the epicenter about 11 kilometers, or seven miles, South East of the city of Izmit. On August 17, 1999, the Mw=7.4 Kocaeli earthquake struck a densely populated region in North Western Turkey, which is also the industrial heartland of the country. This location indicates that the earthquake occurred on the Northernmost strand of the North Anatolian fault system. The earthquake originated at a depth of 17 kilometers, or about 10.5 miles, and caused right-lateral strike-slip movement on the fault. Since the earthquake occurred 3.00 a.m., when most of the people were indoors, the result was a tragedy, causing 17255 dead, 23781 injured, 626 damaged schools, 47 damaged health facilities, 283240 damaged private homes and 41164 damaged working buildings according to formal statistics. In fact, it is estimated that the mortality is, unfortunately, even higher than this figure. Therefore, prediction of the next large earthquake under the NAFZ would be useful. Such a prediction must be rely on the observation of phenomena that relate to large earthquake.

2. Proper Distribution Selection to Determine Earthquake Risk
In the usual studies for determining earthquake risk generally year is used as time unit and classified frequency distribution is used as frequency distribution. In this study day is preferred as time unit and series is preferred as frequency distribution. In this way increase of this study's sensitivity is satisfied (Çelik and Yılmaz, 2002).

Fig.1 shows the area of investigation (NAFZ), Fig.2 shows, NAFZ's 39.00^o – 42.00^o North latitudes and 30.00^0-40.00^0 East longitudes between 1900 and 2000 years.
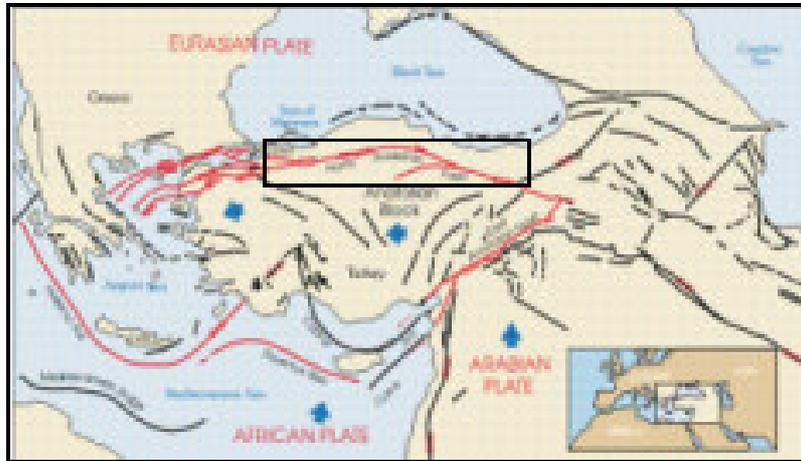
Fig.1 The Area of Investigation (NAFZ)
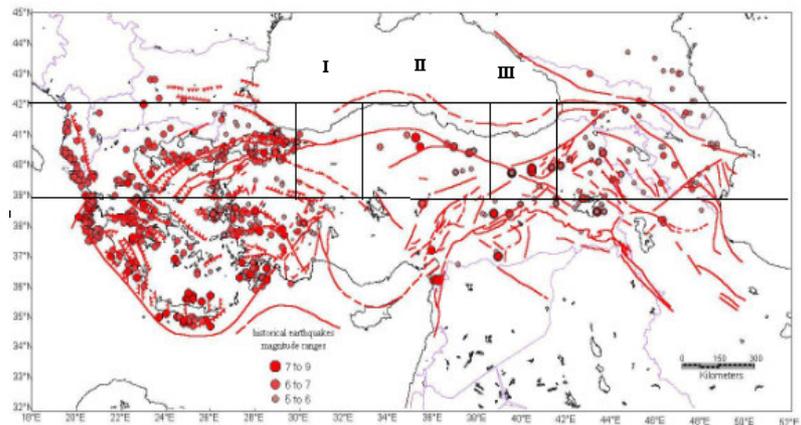**[http://neic.usg.gov/neis/world/turkey].**

Fig.2.The earthquakes occurred in 39.00^{o} - 42.00^{o} North latitude and 30.00^{o}-
40.00^{o} East longitude. (http://neic.usg.gov)

In order to determine proper distribution for the earthquake data set, Kolmogorov-Smirnov test statistics have been calculated and the results are given in Table 1.

Table 1 Kolmogorov-Smirnov Calculation Values

Distribution	Calculated D
Exponential	0.187174
Gamma	0.102502
Log-normal	0.091767
Log-lojistik	0.087780
Weibull	0.065040

Kolmogorov-Smirnov test D Critical table value, the only sampling to compare calculated test statistics, is approximately calculated at 0.05 significance level as given below.

$$D_{n;0.05} = \frac{1.36}{\sqrt{n}}, \ \ n > 35 \tag{1}$$

The critical table value is determined 0.1395 for n=95 and α=0.05 significance level when test statistics are compared with table value it is concluded that in α=0.05 significance level the earthquake data does not fit to exponential distribution among advised distributions. When the calculated test statistics are evaluated it can be said that Weibull distribution should present the earthquake data well. It can be usually seen from P-P plot given Figure 3.
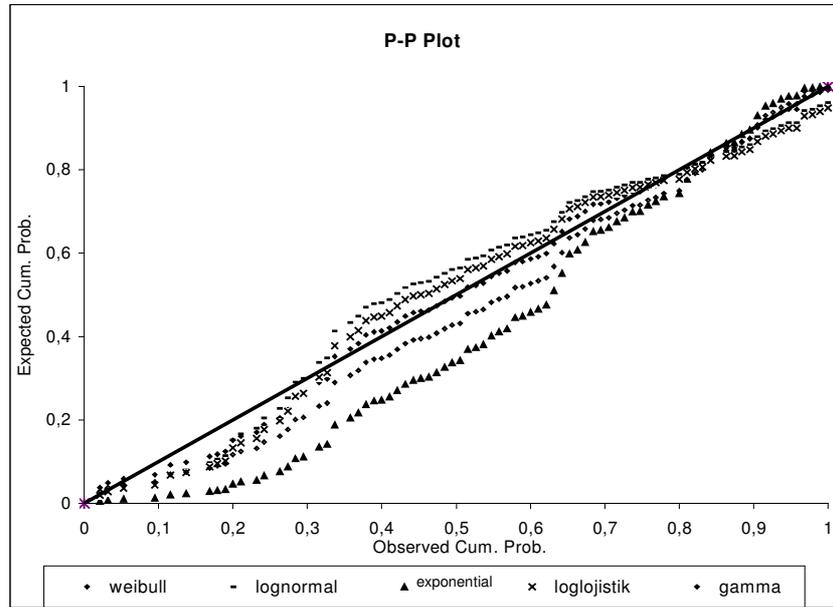

Fig. 3. Plot of probability functions of advised distributions

3. To Determine Earthquake Risk

In modeling earthquake data the most appropriate distribution was established as Weibull Distribution. According to this; when the T random variable is defined as the time (day) elapsed between two earthquakes occurred successively on 39.00°-42.00° North latitude and 30.00° - 40.00° East longitudes of NAFZ, the probability density function of T random variable is: (Yılmaz and Erişoğlu, 2003).

$$f(t;\alpha,\beta) = \beta\alpha^{-\beta}t^{\beta-1}\exp(-\alpha^{-\beta}t^{\beta}). \ \ \ \ 0 < t < \infty, \alpha > 0, \beta > 0 \tag{2}$$

We have the following expressions for cumulative distribution and the reliability function:

$$F(t) = 1 - \exp(\ -(\frac{t}{\alpha})^{\beta}) \tag{3}$$

$$R(t) = \exp(-(\frac{t}{\alpha})^{\beta}) \tag{4}$$

The kth order moment of the two parameter Weibull law can be expressed as

$$E(t^k) = \sum_{i=1}^{k} \alpha^i \Gamma_i \tag{5}$$

Where

$$\Gamma_i = \Gamma(1 + \frac{i}{\beta}) = \int_0^\infty t^{\frac{i}{\beta}} e^{-x} dt \,,$$

is the well-known gamma function. Then the mean,

$$E(t) = \alpha \Gamma(\frac{1}{\beta} + 1) \tag{6}$$

Parameter estimation values and mean occurrence period found by using MLE (Maximum Likelihood Estimation) technique are given in Table-2. By placing the parameter estimation values given in Table 2,

Table 2 Parameter estimation values and mean occurrence period found by using MLE.

$\hat{\beta}$	$\hat{\alpha}$	$E(t)$
0.656625	281.1	379.8027

$$f(t; \alpha, \beta) = (0,6566)(281,1^{-0,6566})t^{0,6566-1} \exp(-281,1^{-0,6566}t^{0,6566}) \tag{7}$$

and earthquake data are well modeled by Weibull distribution (equation 7). The mean occurrence period of earthquakes between 39.00°–42.00° North latitudes and 30.00⁰-40.00⁰ East longitudes which have magnitudes equal to or above 5 is calculated approximately 380 days. So it is expected to have another earthquake having magnitude equal to 5 or above between 39.00°–42.00° North latitudes 30.00⁰-40.00⁰ East longitudes are average 380 days later than the preceding one. Cumulative distribution function graph that shows occurrence risk of an earthquake having magnitude equal to 5 or above in t day(s) after an earthquake occurred between 39.00°–42.00° North latitudes and 30.00°-40.00° East longitudes with magnitudes equal to or above 5 is given in Figure-4
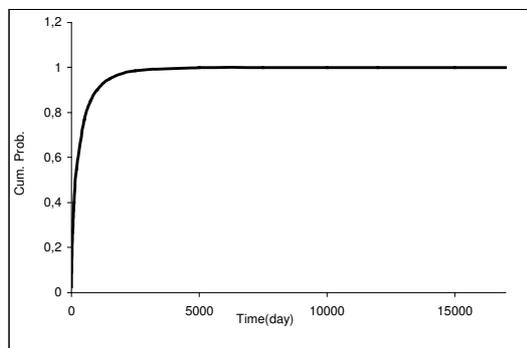

Fig.4. The graph of cumulative distribution function F(t)

The probability of having another earthquake with magnitude 5 or above in 500 days in the investigation area after the preceding one with the same magnitude is 77%. The graph of reliability function that gives the probability of having another earthquake with magnitude 5 or above in t days after the preceding one with the same magnitude between 39.00^{o}–42.00^{o} North latitudes and 30.00^{0}-40.00^{0} East longitudes is given in Figure 5.
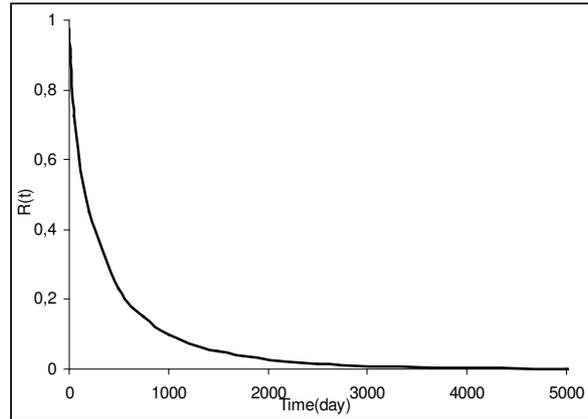

Fig.5.   The graph of reliability function R(t)

In this section of the study, NAFZ has been divided into three areas in terms of different features such as the number of the earthquakes and magnitudes (Fig.2). Risk evaluation has been performed for the three areas individually. By dividing the investigation area, which locates between 39.00^{o}- 42.00^{o} North latitude and 30.00^{o}-40.00^{o} East longitudes of NAFZ, into three as West (I), Middle (II) and East (III), risk-rating can be made in the investigation area. According to this, let the area 30.00^{o}-33.00^{o} in the East longitude be named as Western investigation area, the region between 33.00^{o}-37.00^{o} in the East longitude be named as Middle investigation area, and the area between 37.00^{o}-42.00^{o} in the Eastern longitude be named as East investigation area. MLE has been used in estimating the Weibull Distribution parameters in the investigation areas. The estimation values of the Weibull Distribution parameters and mean occurrence period the for the three investigation areas are given in Table 3.

Table 3. The estimation values of the Weibull Distribution parameters and mean occurrence period the for the three investigation areas.

	West	Middle	East
$\hat{\beta}$	0.48	0.636	0.62
$\hat{\alpha}$	502.976	551.812	1215.55
E(t)	1087.835	772.7963	1754.771

For the examined three investigation area when mean occurrence periods are evaluated. It can be seen that the Middle investigation area has mean occurrence period less than others. For having risk classification of three investigation areas

cumulative distribution function graphs are evaluated in the same axis and are shown in Figure 6.
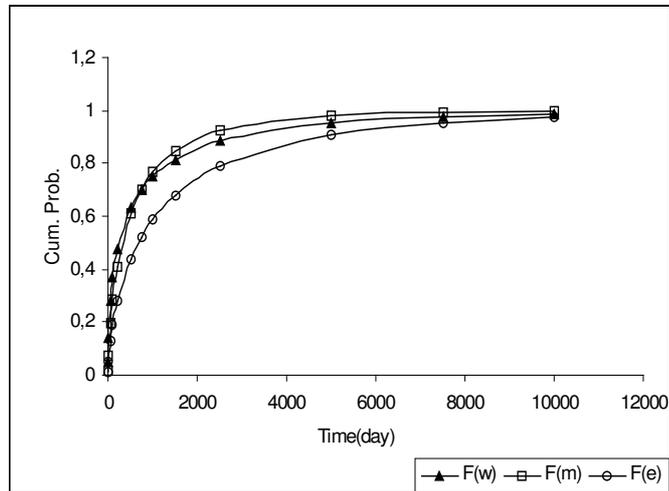

**Fig. 6. Evaluation of three cumulative distribution functions
on the same axis**

4. Conclusion

As a result of this study for determining earthquake risk:
- Weibull distribution is determined as the most appropriate distribution for our data set.
- After an earthquake with magnitude 5 or above, while the West investigation area is the most risky area in the first 750 days. After 750 days Middle investigation area has been detected most risk bearing area.
- East investigation area is less risky relative to West and Middle investigation areas.
- Risks of another earthquake occurrence after the preceding one in a year in West, Middle and East investigation areas are respectively 58%, 54% and 38%.
- Risks of another earthquake occurrence after the preceding one in 5 years in West, Middle and East investigation areas are respectively 84%, 88% and 72%.
- Risk of another earthquake after the preceding one having magnitude 5 or above in investigation area in 100 days is 69% determined as and it is concluded that the region's earthquake risk is too high.
- In risk grading of inside of each part it is concluded that the East investigation area has the least risk.

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