Probabilistic forecast of next earthquake event in Makran subduction zone using Weibull distribution

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Abstract: Earthquake is the most lethal type of natural disaster. Researchers have been working to develop precise earthquake prediction methods to save lives. A statistical investigation is an effective earthquake prediction method because they offer more details about the seismic risk or hazard issue. This study utilizes seismic data from the Makran subduction zone from 1934 to 2017. Probability distributions may be employed to assess the risk of seismic events and earthquake occurrence probability. This work estimates the probability of the next major event in the Makran subduction zone through Weibull distribution by considering strong earthquakes with a magnitude ($M_w \geq 6$) in the intervals (in years) between two consecutive earthquakes. The probabilities of the forthcoming seismic event have been estimated based on the previous earthquake record, pictorially. The calculated parameters of the Weibull distribution for the Makran subduction zone may help to forecast the probabilities of a strong earthquake and describe the pattern of earthquake average return time. The calculated probability for the Weibull distribution reaches 0.92 after ten years since the last strong earthquake in 2021, indicating that the Weibull distribution within and around the present research area in 2031 will be 92%.

Key words: probability distribution, earthquake prediction, Weibull distribution, statistical analysis, seismicity, Makran subduction zone

1. Introduction

According to *Weightman et al. (2011)*, the Japanese city of Fokoshima experienced an earthquake in March 2011, in which several people died. While according to *Deshpande (1987)*, during 1900 − 1976, there were 2.7 million fatalities due to earthquakes. It represents how lethal earthquakes are than any other type of natural disaster. Numerous earth scientists have examined the tectonic and seismic activity of the Makran area and determined it as an active subduction zone (*White and Klitgord, 1976; Page et al., 1979; Quittmeyer and Jacob, 1979; Byrne et al., 1992; Kopp et al., 2000;*

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Wiedicke et al., 2001; Schlüter et al., 2002; Vernant et al., 2004). According to *Yang et al. (2022)*, the convergence rate of the Makran subduction zone is $\sim$38 mm yr^{-1}. The Makran subduction zone has a low dip angle (*Harms et al., 1984; Schlüter et al., 2002; Heidarzadeh et al., 2008*). The Makran subduction zone has two distinct portions with different seismic characteristics. According to *Heidarzadeh et al. (2009)*, in the eastern portion, a historical subduction event occurred in 1945, while no significant subduction event has happened in the western segment yet. If stress emerges from the locked western region of Makran, a subduction seismic event may occur. Earthquakes are very disturbing because they occur suddenly. Therefore, developing advanced techniques for earthquake forecasting might help save lives. A statistical approach might be the best method for estimating future earthquake occurrences. The probability distribution model might help calculate the next large earthquake in any region, even though no theoretical model is available. Numerous earth scientists and statisticians try to forecast future earthquakes. Several researchers have worked on probabilistic predicting the time of the next seismic event on a particular fault for one-quarter century: *Utsu (1972a, 1972b)*, *Hagiwara (1974)*, and *Rikitake (1974)*.

While *Cornell (1968)*, *Caputo (1974)*, *Shah and Movassate (1975)*, *Båth (1979)*, and *Cluff et al. (1980)*, for seismic analysis, utilized Poisson distribution. Several distributions, such as double exponential, Gaussian, Weibull, Log-normal, Gamma, and Pareto distribution models, were suggested by *Utsu (1972b)*, *Rikitake (1974)*, *Hagiwara (1974)*, *Nishenko and Buland (1987)*, *Utsu (1984)*, and Sergio G. Ferráes (*Ferráes, 2003*) for conditional probabilistic estimation of the next seismic event. Three different distributions had utilized by *Tripathi (2006)* and *Yadav et al. (2008)* for the analysis of the time-dependent seismic event in Gujrat, India. Finding accurate distribution for large earthquake data is complicated for a specified fault. According to *McNally and Minster (1981)*, *Yilmaz et al. (2004)*, *Roy (2014)*, *Madan et al. (2019)*, the Weibull distribution model best suits seismic data compared to other distribution models. The Weibull distribution has various implementations in earth science, environmental and medical science. The results of a design degradation experiment conducted by *Ababneh and Ebrahem (2018)* demonstrate that the degradation rate follows the Weibull distribution. This study investigates the Makran subduction zone earthquake data that occurred between 1934 and 2017 with moment magnitude ($M_w \geq 6$). The last strong-magnitude earthquake occurred near Pasni, having a magnitude of 6. As a result of this earthquake, no fatalities occurred, but a few buildings collapsed.

This study aims to predict future large earthquakes in the Makran subduction zone using Weibull distribution. In the current study, the year has taken as the unit of time, and frequency is the frequency distribution for determining earthquake risk. However, some research has taken day as the unit of time. One great earthquake, one major earthquake, and fifteen strong earthquakes struck the Makran subduction zone. There are Six classes of earthquakes based on their magnitude for example, a Minor earthquake may felt ($M_w \geq 3.0$), a Light earthquake trigger minor destruction ($M_w \geq 4.0$), a Moderate may damage structures ($M_w \geq 5.0$), a Strong earthquake may cause destruction in the populated region ($M_w \geq 6.0$), Major earthquake can trigger severe collapse ($M_w \geq 7.0$), and Great earthquake can cause huge destruction ($M_w \geq 8.0$). The Structure of this work is as follows; section 2 discusses the methodology utilizes, section 3 instructs the result of the work, and Section 4 specifies the conclusion.

2. Methodology

Various statistical approaches have been proposed for earthquake forecasting, in which few may be reliable. *Yilmaz et al. (2004)* used different distribution models for future earthquake prediction in the north Anatolian fault zone. They recommended that the Weibull distribution model best fits the seismic data compared to other distribution models. *Roy (2014)* utilized Weibull distribution to predict the waiting time for the next earthquake in Bangladesh. *Chakravorti et al. (2015)* applied three distribution models for predicting earthquakes in Bangladesh and its surrounding area. Seventeen significant earthquakes are taken into account utilizing the Weibull distribution in a case study for statistical analysis demonstration. This work assumes t is a random variable (time interval in years) between two earthquakes in the Makran subduction zone. According to *Fréchet (1927)*, *Stone and Van Heeswijk (1977)*, the probability and cumulative density function of random variable t are given as:

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

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right], \tag{2}$$

and the reliability function and mean of Weibull distribution are given as:

$$R(t) = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right], \tag{3}$$

$$E(t) = \alpha\, \Gamma\left(\frac{1}{\beta} + 1\right), \tag{4}$$

α and β in Eqs. (2) and (3) represent the shape and scale parameters of the distribution.

3. Results

Using statistical techniques, the mean interval for the Makran subduction zone seismic data is 4.5 years. However, the period between 2017 and the previous earthquake was four years. Figure 2 shows the magnitude of the earthquake in the Makran subduction zone. The values of shape, scale, and mean occurrences period calculated for the Makran subduction zone are below:

$\beta = 4.7943,\ \alpha = 1.2051,\ E(t) = 4.50\,.$

We get Eq. (5) by placing these values in Eq. (1). Eq. (5) represents the earthquake data shown by the Weibull distribution is well exhibited. Using Eq. (4), mean occurrences time is calculated. The mean recurrence period for magnitude ≥ 6 is 4.50 years for the Makran subduction zone:

$$f(t;\alpha,\beta) = 4.7943\,(1.2051)^{-4.7943}\, t^{4.7943} \exp(-1.2051^{-4.7943}\, t^{4.7943}), \tag{5}$$

Thus, the Makran subduction zone is expected to experience earthquakes of magnitude ≥ 6 on an average of 4.5 years after the previous earthquake. Recently an earthquake occurred near the Harnai Balochistan region, with a magnitude of 6.0 (M_w) in 2021. As a result of this earthquake, 42 people died, and 300 were injured. The forecast is almost justified based on previous seismic data with a magnitude ≥ 6 up to 2017 for the Makran subduction zone.

We get the new values for shape and scale parameters of the Weibull distribution up upto 2021:

$\beta = 4.7891,\ \alpha = 1.2563,\ E(t) = 4.45\,.$

Adding these values in the equation, the probability density function is:

$$f(t;\alpha,\beta) = 4.7891\,(1.2563)^{-4.7891}\,t^{4.7891-1}\,\exp(-1.2563^{4.7891}\,t^{4.7891}), \qquad (6)$$

Figure 2 represents the occurrences probability of Weibull distribution cumulative function having time interval t in the study region. While the reliability function graph having the possibility of the next earthquake ($M_w \geq 6$) in the Makran subduction zone at time intervals (year) is shown in Fig. 3. There is a 92% probability of earthquake occurrences of magnitude ≥ 6 after the last earthquake ten years later (i.e., 2031) in the Makran subduction zone (Fig. 2). It means that by 2035, there is a 99.9% probability of earthquake occurrences having a magnitude ≥ 6.

4. Conclusion

A statistical approach is essential for seismic risk estimation because earthquakes are random phenomena. By utilizing statistical distribution, one can

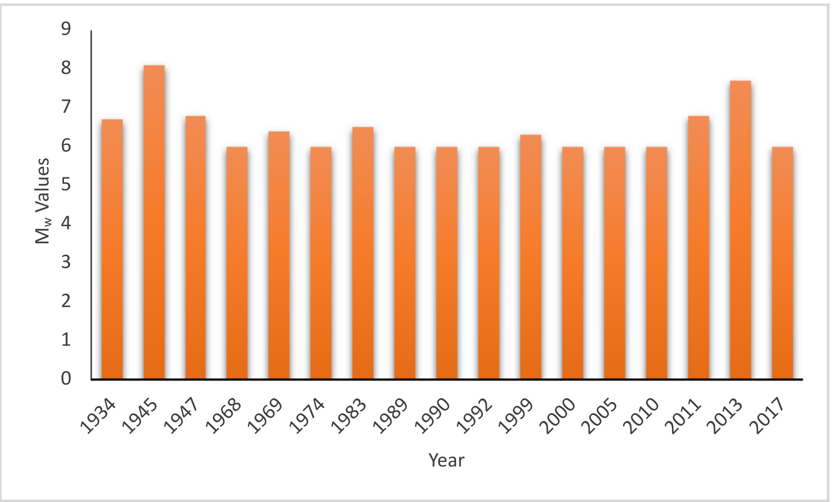

Fig. 1. Time and magnitude plot of earthquake having magnitude ≥ 6.

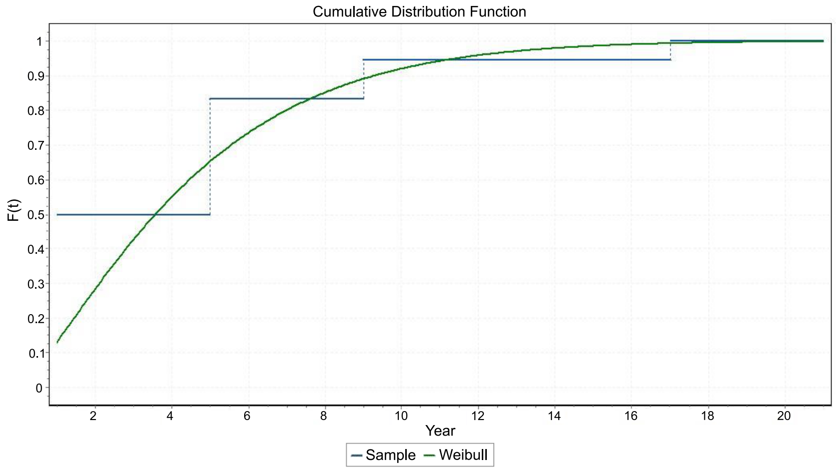

Fig. 2. Weibull distribution cumulative distribution function graph.

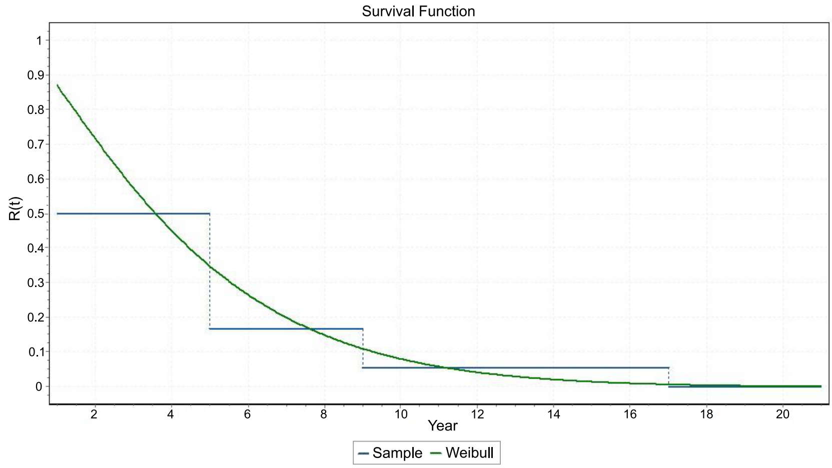

Fig. 3. Weibull distribution reliability graph.

determine the earthquake probability. In the current work, we use Weibull distribution to estimate the mean time of two successive earthquake events on the data set from 1934 to 2017 by considering t (in years) as a random variable. Figure 1 shows that the frequency and magnitude of the earthquake increase with time. The depth of most seismic events is shallow. The mean time for earthquakes with a magnitude greater than or equal to 6 is

4.5 years. The forecast of earthquake data up to the year 2017 is almost reasonable. The mean time estimated for earthquake data up to 2021 is 4.45 years, having a magnitude ≥ 6. It tells us that the next significant earthquake with a magnitude ≥ 6 may occur in about 4.45 years in the Makran subduction zone. It shows that this region is at high risk in the upcoming years. Based on past earthquake data and statistical calculations, we get these results. The result of our study shows that the Weibull distribution is a suitable model for the earthquake data we used.

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