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SEISMIC HAZARD ASSESSMENT AND ANALYSIS IN INDIA: A REVIEW

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Abstract

Seismic hazards are considered one of the most destructive natural threats to infrastructure, human life and economic assets. Over the past decades, extensive research has been conducted to improve earthquake prediction and mitigation strategies, with the aim of minimizing loss of life and damage. Various mathematical, statistical and machine learning approaches have been employed to model and forecast earthquake occurrence using historical and geodetic datasets. Over the past 120 years, India has witnessed a high frequency of earthquakes exceeding magnitude 6.0. India is located near to the boundary where the Indian and Eurasian plates meet, which makes it more prone to earthquakes because these tectonic plates are in constant motion and continuously interact with one another. The objective of this study is to critically examine earthquakes in India and analyse their impacts across various regions.

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1. Introduction

Seismic occurrence, an inherent aspect of Earth's dynamics, manifests as catastrophic and devastating events. The lithosphere, consisting of the Earth's crust and the upper mantle, ranges in thickness from 70 to 100 km and constitutes the Earth's outer shell, which is segmented into large tectonic plates see (Madan et al., 2019). The continuous motion of these tectonic plates results in forceful interactions and leading to abrupt shifts. In certain areas immobilized by friction, resulting in a progressive buildup of stress within the locked zone, stress intensifies proportionally due to this strain, leading to movement or fracturing within the earth's crust. This releases energy as strong seismic waves, resulting in an earthquake. Earthquakes have devastating consequences like harming people, animals and structures. They can also trigger a range of secondary hazards, such as landslides, floods, tsunamis and, in some cases, associated events like fires. Survivors may experience diseases, lack necessities and suffer mental health issues like panic attacks and depression. An earthquake intensity is measured by its magnitude and distance from the epicenter. Earthquake datasets typically comprise multiple magnitude scales, including body wave magnitude (MB), surface wave magnitude (MS), local magnitude (ML) and moment magnitude (MW). Earthquakes are categorized by their depth of origin, either shallow or deep. Shallow earthquakes, typically more frequent occur at depths of up to 300 km, while deep earthquakes occur within the range of 300 to 680 km (Roy, 2014).

An earthquake is overwhelming because it strikes without warning. The development of a reliable earthquake prediction method could provide early warnings resulting in potentially saving lives. Numerous researchers employ various statistical and computational approaches to improve earthquake forecasting. These approaches include statistical distribution methods, such as Utsu(1972a,1972b), Rikitake (1974) and Hagiwara (1974) have proposed utilizing probabilistic approaches to estimate the time of future earthquakes along specific fault lines. Cornell (1968), Caputo (1974), Shah (1975), Bath (1978) and Cluff et al. (1980) used the Poisson distribution in seismicity investigation. Several probability distributions such as Double Exponential, Gaussian, Weibull and Gamma have been used to determine the conditional likelihood of future earthquake events. But choosing the right distribution for a particular active fault zone for given the earthquake data is difficult. McNolly and Minster (1981) proposed the Weibull distribution as a suitable model, while Nishenko and Buland (1987) showed that the log-normal distribution also provides a good fit to earthquake data. Yilmaz et al. (2004), Wu et al. (2019) and Madan et al.(2019) studied that Weibull distribution gives the best appropriate result for earthquake data. Absar (2017) developed a Naive Bayes classifier prediction software to estimate the chance of an earthquake, which helps identify safe and risky areas. Sharma and Bajaj (2021) concluded that Gamma, Inverse-Gaussian, Lognormal and Inverse-Gaussian are best fit on their data. Gupta et al. (2023) and Xu (2025) applied machine learning techniques to earthquake analysis and demonstrated their effectiveness in magnitude forecasting, while highlighting the need for proactive measures to mitigate seismic impacts.

India has experienced several major earthquakes in the past and as a result, half of its land area is prone to damage; in fact, about 59% of the country is considered susceptible to earthquake damage. The northeastern region and the Himalayas are affected by earthquakes of magnitude exceeding 6.0, which are primarily caused by the movement of the Indian plates towards the Eurasian plate at the rate of about 50 mm per year (Jain (1998)). Nath and Thingbaijam (2012) provided a comprehensive probabilistic seismic hazard assessment for India, showing the highest hazard in the Himalayan belt and northeast India and moderate but non-negligible hazard in peninsular India. Ansari et al. (2021) highlight earthquakes have a significant impact on large populations every year, with many experiencing severe damage and even loss of life, showing how dangerous earthquakes can be. The Indian subcontinent has experienced some of the world's most notable earthquakes with magnitudes of 6.0 and higher, such as the Himachal earthquake of 1905 (M_L6.8), the Bihar earthquake of 1934(M_L8.0) , the Andaman and Nicobar Island earthquake of 1941 (M_L8.1), the Bhuj earthquake of 2001 (M_L7.7), the Indian Ocean earthquake of 2004 (M_L9.1), the Kashmir earthquake of 2005 (M_L7.6), the Imphal earthquake of 2016 (M_L6.7) and a few others. This article study about all earthquake zone in India which are more highly risky about largest earthquake in past historical data and analyse their diverse effect in different areas.

Ahadzadeh and Malek (2021) propose a multi-scale earthquake damage assessment framework using machine learning and deep learning, showing that deep learning outperforms traditional classifiers and that social media and spatial data can improve rapid disaster response. Rehman and Zhang (2024) used a Weibull-based probabilistic model for the Makran subduction zone and found a high likelihood of a major earthquake in the coming decades, underscoring the need for urgent preparedness in this tectonically active region. The aim of this study is to give a critical review of earthquakes in India and analyse their varied effects in different areas.

2. A Comprehensive Review of Seismic Zones in India

Magnitude, which gauges how an earthquake affects various locations, is used to determine the seismic zones in India, according to the National Centre of Seismology. According to geographic statistics, 59% of India's territory is at risk of earthquakes. Seismic Zone I, the minimal risk threat zone, was combined with Seismic Zone II, leaving zone I devoid of any region (Bhatia et al., 1999) Based on seismicity levels, India has separated into four seismic zones (II, III, IV and V). Six categories can be used to classify earthquakes based on their magnitude (Madan et al. ,2019).

1. Enormous Earthquake ($M_L \geq 8.0$)-Damages completely the communities near the epicentre.

2.Major Earthquake ($7 \leq M_L \leq 7.9$)-Result in serious damage.

3. Strong Earthquake ($6 \leq M_L \leq 6.9$)- Damages heavily populated areas.

4.Modest Earthquake ($5 \leq M_L \leq 5.9$)-Damage slightly to the buildings and other infrastructures.

5.Light Earthquake ($4 \leq M_L \leq 4.9$)-Result in minor damage.

6. Minor Earthquake ($3 \leq M_L \leq 3.9$)- Causes very slight damage.

This study examines all seismic zones in India.

Zone II

Taking up a substantial 40.93% of the country, it is a minimal destruction risk zone. This includes both the land area completely submerged under water and the Karnataka elevated land area zone.

Zone III

This zone is deemed modest damaged risk zone and covers 30.79% of the country's area. Kerala, Goa, the Lakshadweep Islands, Madhya Pradesh, Bihar, Jharkhand, Chhattisgarh, Maharashtra, Odisha, Tamil Nadu and Punjab are all included in this.

Zone IV

This zone is considered highly damaged risk zone and covers 17.49% of the country. This zone comprises the remaining areas of Himachal Pradesh, Bihar, Delhi, Sikkim, northern Uttar Pradesh, West Bengal, western Maharashtra, Rajasthan and Jammu Kashmir.

Zone V

This zone is an extremely dangerous zone in India and encompasses 10.79% of the country's area. This includes North Bihar, Himachal Pradesh, Uttarakhand, North-East region, the Rann of Kutch in Gujarat and the Andaman and Nicobar Islands.

A regional comparison further shows that seismic hazard in India is not uniformly distributed. The Himalayan belt and northeastern India are generally more vulnerable because of active plate convergence and frequent tectonic disturbances, whereas peninsular India experiences comparatively lower but still significant intraplate seismicity. Coastal regions may also face additional risk from secondary effects such as tsunamis and ground shaking amplification. This regional perspective is important because it provides a more realistic understanding of seismic risk and helps in prioritizing mitigation and preparedness measures across different parts of the country.

Largest earthquake in India India experiences around 200-250 earthquakes annually, however only few are felt by people. Even though the number of earthquakes in India is taken into account, many are of minor magnitude and are not widely reported. India has persisted most damaging earthquakes in the world with magnitude surpassing 6.0 from 1900-2020 as shown in Table 1. The following are some of the most significant earthquakes.

Kangra earthquake (1905)

The Kangra region of Himachal Pradesh was struck by a major earthquake occur in 4th April, 1905 with a great magnitude recorded 7.8 measured on the Richter scale. The epicentre was detected at 33.0 N 76.0 E. It was one of the first major earthquakes in the 20th century in northern India (Middlemiss ,1910). More than 1,00,000 homes destroyed and 20,000 people died. The earthquake was experienced across a wide region, including regions Jammu and Kashmir and Uttarakhand. It caused extended structural damage in these regions.

Bihar earthquake of (1934)

Bihar–Nepal earthquake 1934 was catastrophic earthquake occurred on January 15, 1934 with magnitude 8.0 (Roy,1939). In India's history this earthquake was a very devastating earthquake caused extensive destruction in northern Bihar and Nepal. Close area of Munger and Muzaffarpur were destroyed due to this earthquake. The districts of Champaran, Muzaffarpur, Darbhanga and Bhagalpur were most gravely impacted. The earthquake fault extended from Motihari to Monghyr, a distance of about 135 miles. The earthquake killed more than 10,000 to 12000 peoples.

Andaman and Nicobar Island earthquake (1941)

Andaman Islands earthquake 1941 occurred on June 26, 1941 with magnitude of 7.7 to 8.1. It was the largest earthquake before 2004 on the India-Burma plate boundary. This earthquake damaged the Andaman Islands and triggered a tsunami that affected the Andaman and Nicobar Islands, India and British Ceylon. This earthquake sustained extreme damage to the Andaman Islands. The resulting tsunami led to fatalities along eastern coastline of India. This tsunami also caused destruction and casualties in Bangladesh, Myanmar and Thailand. The central watchtower of the cellular jail in Port Blair collapsed, along with a hospital and other masonry structure.

Assam-Tibet earthquake of (1950)

Assam -Tibet earthquake 1950 occurred on 15 august, 1950 with magnitude 8.0 measured on the Richter scale. The epicentre of this earthquake was recorded at Rima, in Tibet. It is the largest earthquake caused by continental collision rather than subduction. A total 4 ,500 death was recorded and several damaged properties in this earthquake.

Garhwal earthquake (1991)

The northern Indian Garhwal Himalayas had an earthquake on October 20, 1991, around 2.53 a.m. local time. The state of Uttarkashi, Tehri and Chamoli all experienced severe ground shaking as a result of the earthquake. According to official data, there were approximately 307,000 people living in 1,294 villages affected; 768 people lost their lives and 5,066 were injured Jain, S.K et al. (1992). The earthquake also claimed 3,096 cattle heads. Up to forty two,400 homes suffered damage. There was a disruption in the roadways between Uttarkashi and Gangotri. The Indian Institute of Technology, Kanpur's Civil Engineering Department sent a four-person team to survey the severely impacted districts between October 27 and November 4.

Bhuj Earthquake of (2001)

Bhuj earthquake struck Gujarat, India on January 26, 2001 with a magnitude of 7.7. This seismic event killed thousands of people and destruction of numerous buildings and vital infrastructure. The earthquake was triggered by movement along a previously unrecognized fault line. In this earthquake approximately 20,000 people died, 167,000 were injured and it destroyed nearly 400,000 homes across several districts. It severely damaged essential infrastructure like hospitals, roads, bridges, power and water systems. The historic Swaminarayan temple, historic forts, Prag Mahal and Aina Mahal were partially damaged.

Indian Ocean Earthquake (2004)

The Indian Ocean earthquake is a catastrophic event which struck on 26 December,2004 also known as Boxing Day. The earthquake magnitude ranged from 9.2 to 9.3 and the earthquake epicentre was located off the western coast of Sumatra, Indonesia Ansari et al. (2021). The resulting tsunami killed over 220,000 people. The earthquake breaks off the fracture at the point where the Indian tectonic plate slides under the Burma plate. The breaks off was exceptionally extensive, extending 1,600 kilometre's and shifting 15 meters. The break generated a series of waves that reached 30 meters in height. The waves propagated at a speed of approximately 80 kilometres per hour in shallow water. The worst impact was felt in Indonesia and Sri Lanka. Other countries affected include Malaysia, Maldives, Myanmar, Seychelles, Thailand and Somalia.

Sikkim Earthquake (2011)

The Sikkim earthquake occurred on 18 September 2011, registering a magnitude of 6.9. Its epicentre was located in the Kanchenjunga Conservation Area, near the border between Nepal and the Indian state of Sikkim. The tremors were felt across northeastern India, Nepal, Bhutan, Bangladesh and southern Tibet. The earthquake resulted in the loss of at least 111 lives and caused significant damage to property.

3. Seismic Hazard Analysis

Seismic hazard analysis and risk assessment in India are critical areas of research, it helps to identify area of high seismic risk, informs the ideas about mitigate and preparedness. Seismic hazard analysis evaluates the potential for earthquakes across the nationwide by examining its various tectonic plates, identifying active fault zones and determining the probability of strong ground shaking at various locations. This analysis primarily focusing on the highly seismic field like the Himalayas, the Indo-Myanmar arc and the Shillong Plateau, which are classified into different seismic zones behalf on their earthquake risk level with Zone V indicating the highest hazard level, this analysis is crucial for designing earthquake-fortified structure and contingency planning. Figure 1 represented the India's four seismic zone in different colours. The data have been taken from official site of Bureau of Indian Standards (2025) https://www.bis.gov.in/. To analyse the seismic hazard rates, two methods are employed: Deterministic and probabilistic approaches, namely DSHA and PSHA, are the two main methods employed in seismic hazard analysis(Mehta et al. 2017).

• (DSHA) Deterministic Seismic Hazard Analysis, as discussed by Sharma (2024) and Das et al. (2025), evaluates the maximum ground motion at a site by considering a worst case earthquake scenario associated with a known seismic source. It typically focuses on the largest credible earthquake and provides a single estimate of the maximum expected seismic intensity, commonly expressed in terms of Peak Ground Acceleration (PGA). This approach is particularly suitable for the design of critical infrastructure, such as dams and nuclear power plants, where safety considerations are paramount. However, DSHA does not account for the probability of occurrence or the temporal frequency of such events.

• In contrast, (PSHA) Probabilistic Seismic Hazard Analysis (Sharma, 2024) quantifies seismic hazard probabilistically by incorporating earthquake frequency, magnitude distribution and associated uncertainties. It integrates contributions from all potential seismic sources, considering a range of magnitudes and their associated occurrence rates. In PSHA, results are typically presented as seismic hazard curves that quantify the probability of exceeding a particular ground motion level within a specified time frame. This method is widely employed in seismic design codes, urban planning and risk management, where maintaining an optimal balance between safety and economic considerations is critical. Owing to its ability to account for uncertainties and temporal variability, PSHA provides a more comprehensive assessment of seismic hazard over time.

4. Data Analysis

There are different types of methods for earthquake prediction, statistical method is one of them. Here we have used the statistical method for forecasting the earthquake in India and its surroundings. For this purpose, we choose the Weibull distribution, Log-normal distribution and Exponential distribution. The PDF for a Weibull distribution is given by (Yilmaz and Celik (2008))

$$F(t;\alpha,\beta) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}}, \quad t \geq 0, \alpha,\beta > 0 \qquad ....(4.1)$$

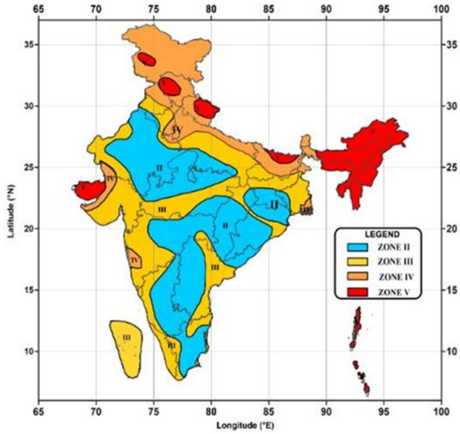

Figure 1. Bureau of Indian Standards (2025) https://www.bis.gov.in/.

Equation (1) alpha, beta are the fitting parameters of the distribution. The cumulative distribution function for a Weibull distribution is given

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^{\beta}}, \quad t \geq 0,\ \alpha, \beta > 0........(4.2)$$

According to Chakravorti et al. (2015), the PDF for Log-normal distribution is

$$F(t;\mu,\sigma) = \frac{1}{t\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln t - \mu)^2}{2\sigma^2}\right), \quad t > 0; \sigma > 0.....(4.3)$$

where mu represent mean and sigma represent standard deviation. And Cumulative distribution function of the Log-normal distribution is given by

$$F(t) = \Phi\left(\frac{\ln t - \mu}{\sigma}\right).....(4.4)$$

The exponential distribution is defined using the rate parameter lembda as follows

$$F(t) = \lambda e^{-\lambda t}, \quad t \geq 0,\ \lambda > 0.....(4.5)$$

And the CDF of the exponential distribution is given by

$$F(t) = 1 - e^{-\lambda t}, \quad t \geq 0,\ \lambda > 0......(4.6)$$

For this statistical analysis, earthquake data presented in Table 2 has been examined. Only earthquakes with a magnitude of 6 or higher have been considered, as such events can cause significant damage to infrastructure and may result in loss of life among both humans and animals. Using this dataset, the average time interval between two consecutive earthquakes was calculated and it was found to be approximately 6.105 years. The parameters estimated by MLE method and found that Weibull parameters are beta approx 1.07 and alpha approx 6.29, Lognormal parameters are mu approx 1.55 and sigma approx 0.78 and Exponential rate parameter is 0.163. Since the Weibull shape parameter is close to 1, it indicates that earthquake occurrences follow a random pattern.

TABLE 1. Kolmogorov–Smirnov test statistics

Distribution	Calculated D
Weibull	0.118948976
Lognormal	0.232413275
Exponential	0.099902729

To determine the most appropriate distribution for the earthquake dataset, the Kolmogorov Smirnov (KS) test statistic was computed and the results are presented in Table 1. The critical value (D) was calculated for a sample size of n = 19 at a significance level of 0.05 and the test statistic was compared with the tabulated values.

It is evident from Table 1 that all calculated D values are less than the critical value, indicating that all the considered distributions are applicable to the given dataset.

The fitted statistical distributions are evaluated using the Kolmogorov–Smirnov goodness-of fit test to assess how well each model represents the observed earthquake recurrence data. This evaluation provides an objective basis for comparing the candidate distributions and identifying the most suitable model for the dataset. In addition, performance measures such as RMSE, MAE, accuracy, precision, recall, or ROC-AUC may be incorporated in future extensions of the study to further strengthen the quantitative assessment of model fit and predictive usefulness.

Visualization analysis

To support interpretation, the study includes visual representations such as temporal plots, magnitude-frequency distributions and regional hazard maps. These help identify patterns in seismic occurrence and provide a clearer understanding of the spatial and statistical behaviour of earthquakes.

Perspectives on Magnitude Distribution

Strong earthquakes dominate at 50%, followed by Major at 25%, Great at 20%, and Modest at 5%. This emphasizes the need for improved probabilistic seismic hazard modelling utilizing distributions like Weibull and shows India's susceptibility to severe disasters especially in high-seismic zones like the Himalayas and Northeast. Zone V locations, where large earthquakes offer severe dangers, should be given priority in future mitigation efforts.

5. Comparision Between Machine Learning Technique and Statistical Probability Distribution

Machine learning techniques and statistical probability distributions in earthquake studies both of them play important but distinct role. Statistical distribution such as Lognormal, Weibull and Exponential distributions are commonly used to study

TABLE 2. Major earthquakes in India (1900–2021) with date, magnitude, and depth

Sr. No.	Date	Name of Earthquake	Magnitude	Depth (km)
1	4 April 1905	Kangra earthquake	7.8	6
2	15 January 1934	Bihar earthquake	8.0	10
3	26 June 1941	Andaman and Nicobar earthquake	8.1	49
4	15 August 1950	Assam–Tibet earthquake	8.0	15
5	21 July 1956	Anjar earthquake	6.1	15
6	11 December 1967	Koyna earthquake	6.6	15
7	19 January 1975	Kinnaur earthquake	6.8	25
8	20 October 1991	Uttarkashi earthquake	6.8	12
9	30 September 1993	Latur earthquake	6.4	10
10	22 May 1997	Jabalpur earthquake	6.0	22
11	29 March 1999	Chamoli earthquake	6.8	15
12	26 January 2001	Bhuj earthquake	7.7	17
13	24 December 2004	Indian Ocean earthquake	9.1	30
14	8 October 2005	Kashmir earthquake	7.6	15
15	14 February 2006	Sikkim earthquake	5.3	20
16	10 September 2009	Andaman Islands earthquake	7.5	24
17	18 September 2011	Sikkim earthquake	6.9	19
18	25 April 2015	India–Nepal earthquake	7.8	8
19	4 January 2016	Imphal earthquake	6.7	58
20	28 April 2021	Assam earthquake	6.0	34

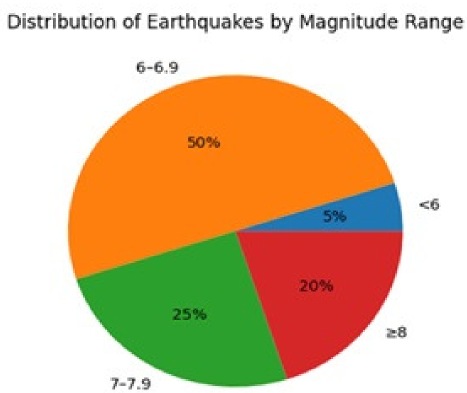

FIGURE 2. Distribution of Earthquakes by Magnitude Range

earthquake occurrence patterns, estimate return periods and quantify uncertainty in a clear and interpretable manner. These approaches are relatively simple, require less data and provide strong probabilistic understanding, although they may not effectively capture complex and nonlinear patterns in seismic behaviour.

On the other hand, machine learning methods, including neural networks, support vector machines and decision trees, are designed to extract hidden patterns from large and complex datasets, making them highly useful for earthquake prediction, classification and real-time monitoring. However, these models often demand large datasets, higher computational resources and can be difficult to interpret. Therefore, while statistical methods are well-suited for risk assessment and probabilistic analysis, machine learning provides enhanced predictive power and combining both approaches can lead to more accurate and reliable earthquake analysis.

6. Result and Conclusion

The statistical results indicate that earthquake recurrence in the studied dataset follows a pattern that is close to random, as suggested by the Weibull shape parameter being near unity. This finding should be interpreted in the context of tectonic activity, fault interactions and the complex geophysical processes that govern seismic events in India. Rather than viewing the fitted parameters only as numerical outputs, the results provide insight into the underlying recurrence behaviour and support a broader geological interpretation of seismic risk.

India is highly prone to earthquakes, with thousands of events recorded over the years, including several damaging ones. Different analytical techniques are used to study earthquake data and different methods fit in different data. Earthquake risk can be reduced through earthquake-resistant construction and proper safety measures. In the future, combining machine learning with statistical methods can improve prediction accuracy by capturing both complex patterns and uncertainties, while AI-based systems can support early warning and disaster preparedness, despite challenges in precise prediction.

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