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A Predictive Model for Quantitative Determination of Seismic Hazard Probability

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Abstract: **It is estimated that 60 % of the Indian landmass is susceptible to earthquakes of moderate to very high intensity. Earthquakes can disrupt progress and destroy the outcome of developmental efforts over several years. The loss in terms of private and public assets is astronomical, pushing the country back economically by several decades.**

Scientific advancements have made it possible to foretell almost all natural disasters with fair degree of accuracy in terms of geographical coverage, likely time of impact and duration of sustenance. However, technology has not yet reached a level where the occurrence of earthquakes can be predicted.

Earthquakes may have widely varying impacts. For example, an earthquake of Magnitude 5 on the Richter Scale might inflict much more damage than an earthquake of magnitude 6 depending on the epicenter and other geographical and infrastructural variables.

In view of the above, the need to evolve an effective quantitative measure of the seismic hazard needs no emphasis. There is, thus, a need to develop metrics, based on rigorous mathematical model, which can be used and interpreted appropriately.

This paper proposes a predictive model for quantitative determination of Seismic Hazard Probability based on the likely occurrence of the quake and facilitates direct comparison of the relative seismic risk in different parts of the country.

Keywords: **Earthquakes, Peak Ground Acceleration, Seismic Hazard, Seismic Zoning Map, Probabilistic Seismic Hazard Analysis, Seismic Hazard Probability.**

I. INTRODUCTION

Prevention of earthquakes is not yet within the realms of available technology and very little can be done to change the incidence or intensity of the earthquakes. Based on analysis of all major earthquakes in the region, the trend that emerges is that longer the time elapsed since the last big earthquake, higher the possibility of the next quake unleashing more devastation. Thus, Indian subcontinent is virtually sitting on a ticking bomb.

All seismic hazards need not necessarily result in a disaster e.g an earthquake hitting an unpopulated or sparsely populated area. While the Disaster Management Act, 2005 lays down institutional and coordination mechanisms towards tackling disasters at the national, state, and district levels, there is no model to conceptualize and measure the disaster in quantitative terms.

The first step towards providing an objective evaluation of seismic hazard is to evolve a quantitative measure of the hazard itself. This is achieved by calculating the seismic hazard probability by summarizing a considerable amount of technical information categorized into mathematical equations.

In this paper the quantitative determination of seismic hazard probability has been proposed, to a large extent, based on historical data and mathematical modeling. These could be validated and refined periodically as an ongoing process.

II. SEISMIC ZONING MAP

The Geological Survey of India (GSI) first published the Seismic Zoning Map of the country in the year 1935 based on the amount of damage suffered by the different regions of India because of earthquakes. Based on the likely Peak Ground Acceleration (PGA) values in a region, it divided the country into five Seismic Zones as under:-

Table 1 : Seismic Zones vis a vis likely PGA

Zone	Likely PGA	Associated Risk
1	< 0.10g	Safe Zone
2	0.10g	Low Damage Risk Zone
3	0.16g	Moderate Damage Risk Zone
4	0.24g	High Damage Risk Zone
5	0.36g	Very High Damage Risk Zone

However, the latest version of Seismic Hazard Map given in the earthquake resistant design code of India [IS 1893 (Part 1) 2002] merged erstwhile Zone I and Zone II and redrew the Seismic Zones as shown in Fig 1.

Theoretically, it is feasible to calculate the seismic hazard probability for any geographical region solely based on PGA. Since Zone 1 is considered safe, its hazard probability would be very low. The rest of the country would have only four discrete values of hazard probability based on the four seismic zones viz Zones 2 to 5. This is neither desirable nor acceptable. Moreover, the present seismic zone map of India has the following limitations:-

- It is based on observed damaged patterns of historical events where the spatial and temporal uncertainty in the occurrence of earthquakes is not included.
- The effects of potential faults have been ignored.

III. PROBABILISTIC SEISMIC HAZARD ANALYSIS

Earthquakes, though rare, cause much of the structural damage due to ground vibration or motion. Probabilistic Seismic Hazard Analysis (PHSA) is based on the following two premises:-

- The seismic hazard or the potential of a site to experience ground motion due to an earthquake cannot be altered.
- The seismic potential at a site can be quantified probabilistically based on recurrence relations, fault lengths and potential maximum magnitude.

In 2007, NDMA undertook PHSA of the country in collaboration with leading institutions like Structural Engineering Research Centre (SERC), Chennai, one of the national laboratories under the Council of Scientific and Industrial Research (CSIR), India, Indian Institute of Technology (IIT), Madras, Indian Institute of Science (IISc), Bangalore, National Geophysical Research Institute (NGRI), India Meteorological Department (IMD), Geological Survey of India (GSI) and Institute of Seismological Research (ISR) to develop the Probabilistic Seismic Hazard Map of the Indian subcontinent.

The sub-continental scale and the spatial variations entailed discretizing the Indian land mass into grids size of 0.2^0 x 0.2^0. Then using state-of-the-art methodology, commonly used all over the world, the Steering Committee, constituted by NDMA, submitted the '*Technical Report on PHSA*' in April 2011. Based on historical seismicity, tectonic features and geology, it divided the subcontinent into 32 Seismogenic Zones as shown in Fig 2.

The comprehensive quantification of seismic activity for the whole country can be characterized by three major parameters:-

- **$N_{(m)}$:** Number of earthquakes greater than or equal to magnitude '*m*' per year. Since earthquakes with magnitude less than 4 do not cause structural damage, the threshold magnitude '*m*' is taken as $\geq$ 4.
- **M_{max} :** Potential maximum magnitude. $4 < M_{max} < 9$.

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- **b :** Although the value of *b* varies from region to region, typically it lies in the range 0.6 < b < 1.5. A lower *'b'* value means that out of the total number of earthquakes, a larger fraction occurs at the higher magnitudes, whereas a higher *'b'* value implies a larger fraction of low magnitude.

Fig 1 : Seismic Zone Map

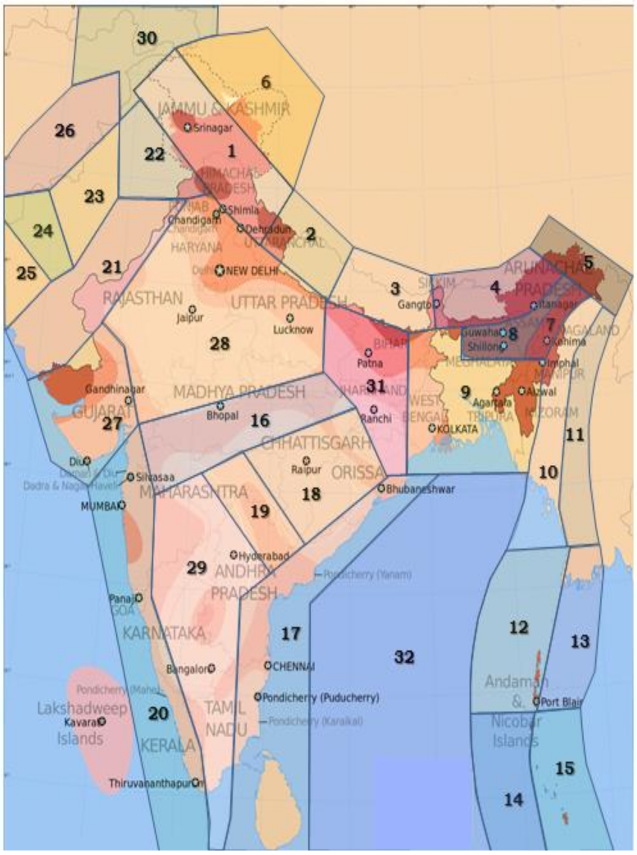

Fig 2 : Probabilistic Seismogenic Zone Map

The three seismic parameters *'$N_{(m)}$'*, *'M_{max}'* and *'b'* for all the 32 seismogenic zones are tabulated below:-

Table 2 : Seismic Parameters for 32 Seismogenic Zones

Zone	Zone Name	$N_{(4)}$	M_{max}	b
1	Western Himalaya	5.37	8.8	0.88 ± 0.02
2	Central Himalaya-I	3.15	7.8	0.73 ± 0.04
3	Central Himalaya-II	2.30	8.8	0.78 ± 0.04
4	Eastern Himalaya	3.12	8.0	0.71 ± 0.04
5	Mishmi Block	3.72	8.8	0.66 ± 0.03
6	Altya Tegh & Karakoram	7.10	7.3	0.91 ± 0.03
7	Naga Thrust	0.18	6.8	0.67 ± 0.08
8	Shillong Plateau & Assam Valley	1.46	8.4	0.73 ± 0.04
9	Bengal Basin	1.99	8.1	0.74 ± 0.04
10	Indo-Burmese Arc	11.40	7.8	0.80 ± 0.02
11	Shan-Sagaing Fault	5.28	8.1	0.66 ± 0.04
12	West Andaman-I	3.62	8.4	0.70 ± 0.03
13	East Andaman-I	5.83	7.5	0.63 ± 0.03
14	West Andaman-II	2.55	7.5	0.71 ± 0.02
15	East Andaman-II	16.53	7.6	0.62 ± 0.01

Zone	Zone Name	$N_{(4)}$	M_{max}	b
16	SONATA	0.24	6.8	0.64 ± 0.08
17	Eastern Passive Margin	0.27	6.1	0.74 ± 0.08
18	Mahanandi Graben & Eastern Craton	0.24	5.3	0.77 ± 0.09
19	Godavari Graben	0.13	6.0	0.85 ± 0.09
20	Western Passive Margin	0.37	6.8	0.76 ± 0.07
21	Sindh-Punjab	0.60	8.0	0.77 ± 0.06
22	Upper Punjab	1.68	7.8	1.01 ± 0.05
23	Koh-e-Sulaiman	5.03	7.3	0.84 ± 0.04
24	Quetta-Sibi	5.22	7.8	0.74 ± 0.04
25	Southern Baluchistan	2.58	7.3	0.74 ± 0.05
26	Eastern Afghanistan	5.59	8.3	0.89 ± 0.04
27	Gujarat Region	1.31	8.0	0.87 ± 0.06
28	Gangetic Region	1.16	7.0	0.81 ± 0.06
29	Southern Craton	0.47	6.8	1.19 ± 0.08
30	Hindukush & Pamirs	83.54	8.0	0.93 ± 0.01
31	Gangetic Region	0.17	6.3	0.84 ± 0.09
32	Bay of Bengal	0.49	6.7	0.60 ± 0.08

IV. EVALUATION OF SEISMIC HAZARD PROBABILITY

Quantifying the hazard entails estimating the probability of occurrence of an earthquake at a given location that threatens to adversely affect human life, property or environment. An attempt has been made to probabilistically model earthquake occurrence probabilities using *'$N_{(m)}$'*, *'M_{max}'*, and *'b'*.

Since occurrences of earthquakes are random phenomena, they can best be predicted by using different probability distributions. After examining several distributions, it emerges that *Poisson Probability Distribution* and Beta *Probability Distribution* are the most appropriate to realistically represent the earthquake occurrence based solely on the three aforementioned values.

Poisson Probability Distribution:

The probability distribution of a Poisson random variable (x) representing the number of successes occurring in a given time interval is given by the formula:-

$$P(x) = \frac{e^{-\mu}\ \mu^{x}}{x!}$$

where $x = 0, 1, 2, 3\ldots$

$e = 2.71828$

μ = *Mean number of successes in the given time interval*

Since $N_{(4)}$ denotes the number of earthquakes greater than or equal to magnitude 4 per year at any location / zone, the probability that no earthquake of magnitude ≥ 4 will occur in a particular zone in any given year is given by:-

$$P_{(0)} = \frac{e^{-N_{(4)}}\ {N_{(4)}}^{0}}{0!} = e^{-N_{(4)}}$$

Thus, the probability that at least one earthquake will occur in a particular zone in any given year is given by:-

$$P_{(\geq 1)} = 1 - e^{-N_{(4)}}$$

The probability of a particular zone experiencing at least one earthquake of magnitude ≥ 4 in a year is given at Table 3.

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Beta Probability Distribution:

Probability Density Function of a standard Beta Distribution is given by

$$f(x) = \frac{x^{\alpha-1}\,(1-x)^{\beta-1}}{B_{(\alpha,\beta)}} \qquad 0 \leq x \leq 1$$

where $B_{(\alpha,\beta)} = \int_0^1 t^{\alpha-1}(1-t)^{\beta-1}\,dt$

and α, β are shape parameters > 0.

A higher value of *'α'* and a lower value of *'β'* results in the Beta Function being right skewed. Alternately, a lower value of *'α'* and a higher value of *'β'* results in the Beta Function being left skewed. Other important statistical functions associated with standard Beta Distribution are listed below:-

$$\text{Mean} = \frac{\alpha}{(\alpha + \beta)}$$

$$\text{Standard Deviation } (\sigma) = \sqrt{\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}}$$

Chebyshev's Theorem states that at least $1 - \frac{1}{K^2}$ of data from a sample must fall within *'K'* Standard Deviations from the Mean, where *'K'* is any positive real number greater than 1. It can be derived from the theorem that for $K = \sqrt{2}$, 50% of the samples of any Beta Probability Distribution will fall within *Mean* $\pm\ \sqrt{2}\sigma$ where *'σ'* denotes the Standard Deviation. For a standard Beta Distribution where Mean = 0.5 and α = β = 4.95, *'σ'* works out to 0.099. Thus, *Mean* $\pm\ \sqrt{2}\sigma$ *implies* 50% of the samples will lie between 0.36 and 0.64 as shown in Fig 3.

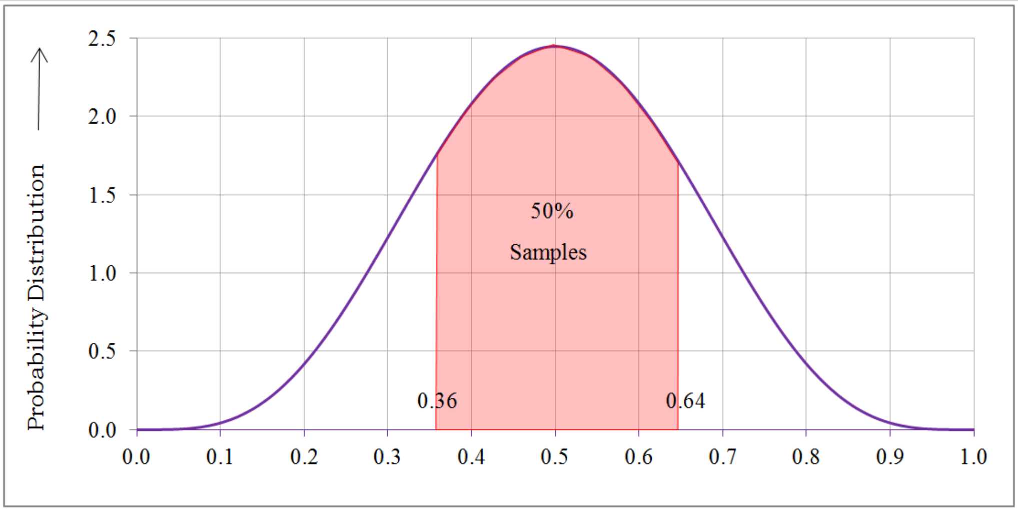

Fig 3 : Standard Beta Probability Distribution

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Probability Density Function of a generalized Beta Distribution having lower and upper bounds other than 0 and 1 respectively is given by

$$f(x) = \frac{(x-L)^{\alpha-1}\,(U-x)^{\beta-1}}{B_{(\alpha,\beta)}(U-L)^{\alpha+\beta-1}} \qquad L \leq x \leq U$$

where L = Lower Bound = 4, since earthquakes with magnitude < 4 do not have any significant effect.

U = Upper Bound = M_{max} (denotes potential maximum magnitude of any seismic zone. 4 < M_{max} <9).

α, β = Shape Parameters.

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Since *'b'* ranges from 0.6 to 1.5, the centre value works out to ($\frac{0.6+1.5}{2}$) = 1.05. Mathematically, the relation between *'α'*, *'β'* and *'b'* can be expressed as:-

$$\alpha = 4.95 + (1.05 - b)$$

$$\beta = 4.95 - (1.05 - b)$$

The Cumulative Distribution Function of the standard Beta Distribution, also called the incomplete Beta Function Ratio (commonly denoted by I_x) is defined as

$$F(x) = I_x(\alpha,\beta) = \frac{\int_0^x t^{\alpha-1}(1-t)^{\beta-1}\,dt}{B(\alpha,\beta)} \qquad 0 \le x \le 1$$

Earthquakes of magnitude less than 5.0 on the Richter Scale are considered minor or light in nature and cause insignificant damage, if any. Earthquakes of Magnitude 5.0 and above are the ones which are felt by most. They may also cause slight damage to ordinary buildings. In a given zone, the probability of earthquakes greater than magnitude 5.0 can be calculated from the Cumulative Distribution Function stated above.

Seismic Hazard Probability:

Seismic Hazard Probability can be defined, in quantitative terms, as the probability (expressed in percent) of a particular place experiencing at least one earthquake of magnitude $\geq$ 5.0. It is given by:-

Seismic Hazard Probability = $P_{(1)} \times P_{(\geq 5)}$

where $P_{(1)}$ = *Probability of at least one earthquake greater than the threshold magnitude 4.0 occurring in a given zone/location.*

$P_{(\geq 5)}$ = *Percentage of likely earthquakes of magnitude $\geq$ 5.0.*

Seismic Hazard Probability of the 32 Seismogenic Zones is given at Table 3.

Table 3 : Seismic Hazard Probability of 32 Zones

Zone	Zone Name	$N_{(4)}$	$P_{(1)}$	M_{max}	b	% of Quakes > M_5	Hazard Probability (%)
1	Western Himalaya	5.37	**0.995**	8.8	0.88	**98.21**	**97.75**
2	Central Himalaya-I	3.15	**0.957**	7.8	0.73	**96.18**	**92.06**
3	Central Himalaya-II	2.30	**0.900**	8.8	0.78	**98.49**	**88.62**
4	Eastern Himalaya	3.12	**0.956**	8.0	0.71	**96.97**	**92.69**
5	Mishmi Block	3.72	**0.976**	8.8	0.66	**98.78**	**96.38**
6	Altya Tegh & Karakoram	7.10	**0.999**	7.3	0.91	**91.33**	**91.26**
7	Naga Thrust	0.18	**0.165**	6.8	0.67	**87.62**	**14.43**
8	Shillong Plateau & Assam Valley	1.46	**0.768**	8.4	0.73	**97.91**	**75.18**
9	Bengal Basin	1.99	**0.863**	8.1	0.74	**97.15**	**83.87**
10	Indo-Burmese Arc	11.40	**1.000**	7.8	0.80	**95.77**	**95.77**
11	Shan-Sagaing Fault	5.28	**0.995**	8.1	0.66	**97.48**	**96.99**
12	West Andaman-I	3.62	**0.973**	8.4	0.70	**98.01**	**95.39**
13	East Andaman-I	5.83	**0.997**	7.5	0.63	**95.18**	**94.91**

Zone	Zone Name	$N_{(4)}$	$P_{(1)}$	M_{max}	b	% of Quakes > M_5	Hazard Probability (%)
14	West Andaman-II	2.55	**0.922**	7.5	0.71	**94.62**	**87.23**
15	East Andaman-II	16.53	**1.000**	7.6	0.62	**95.80**	**95.80**
16	SONATA (Son-Narmada-Tapti)	0.24	**0.213**	6.8	0.64	**88.03**	**18.78**
17	Eastern Passive Margin	0.27	**0.237**	6.1	0.74	**63.80**	**15.10**
18	Mahanandi Graben & Eastern Craton	0.24	**0.213**	5.3	0.77	**5.53**	**1.18**
19	Godavari Graben	0.13	**0.122**	6.0	0.85	**55.28**	**6.74**
20	Western Passive Margin	0.37	**0.309**	6.8	0.76	**86.36**	**26.71**
21	Sindh-Punjab	0.60	**0.451**	8.0	0.77	**96.68**	**43.62**
22	Upper Punjab	1.68	**0.814**	7.8	1.01	**94.33**	**76.75**
23	Koh-e-Sulaiman	5.03	**0.993**	7.3	0.84	**92.05**	**91.45**
24	Quetta-Sibi	5.22	**0.995**	7.8	0.74	**96.13**	**95.61**
25	Southern Baluchistan	2.58	**0.924**	7.3	0.74	**93.00**	**85.95**
26	Eastern Afghanistan	5.59	**0.996**	8.3	0.89	**97.10**	**96.74**
27	Gujarat Region	1.31	**0.730**	8.0	0.87	**96.15**	**70.21**
28	Gangetic Region	1.16	**0.687**	7.0	0.81	**88.93**	**61.05**
29	Southern Craton	0.47	**0.375**	6.8	1.19	**79.09**	**29.66**
30	Hindukush & Pamirs	83.54	**1.000**	8.0	0.93	**95.80**	**95.80**
31	Gangetic Region	0.17	**0.156**	6.3	0.84	**70.75**	**11.06**
32	Bay of Bengal	0.49	**0.387**	6.7	0.60	**86.68**	**33.58**

V. CONCLUSION

India is witnessing an increasing trend of high intensity earthquakes, with nine damaging ones occurring during the last two decades itself. Despite this, there is a general apathy towards disaster preparedness. This can possibly be attributed to the fact that earthquakes are low probability events and hence way down in the priorities of daily living. There is also a reluctance to make preparations that require substantial financial and time commitment.

Presently, the process of risk assessment in India, which deals with probabilities and uncertainties, is largely intuitive. The evaluation of the Seismic Hazard Probability is expected to assist in reducing these uncertainties and provide the following:-

- Quantitative measure of the risk and its potential impact upon life, property and environment.
- Identification of important contributors to seismic risks and quantitative comparison of various earthquake preparedness options and approaches.
- Formulating plans to minimize damage by proper infrastructure planning and following appropriate construction procedures according to the earthquake resistant designs.

- Optimize emergency response in the event of an earthquake.

Since seismicity is dependent on tectonic features and geology of any site, the Seismic Hazard Probability, once worked out, is unlikely to change for a long time.

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