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ON USING MODIFIED MERCALLI INTENSITY DATA FOR EVALUATING ENGINEERING SEISMIC RISK IN NORTHERN INDIA

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ABSTRACT

A probabilistic model, which makes use of Modified Mercalli Intensity data, has been developed for evaluating seismic risk in Northern India. This model predicts the probability of exceedance of any specified earthquake ground motion amplitude (peak amplitudes or spectra) from all the earthquakes expected during some selected future period in the region around the site of interest and does not use only a single design earthquake. All the physical parameters like seismicity in various seismic source zones and the attenuation from source to site, which have inherent uncertainties in their description, have been treated probabilistically. Thus the randomness in the physical processes and the lack of knowledge about them have been accounted for in this presentation. An intensity attenuation model, which can give the probability of occurrence of any intensity at any epicentral distance has been developed first. This provides input for the risk model.

INTRODUCTION

There is no strong motion accelerogram data base in India to analyse the engineering seismic risk for important structures like Nuclear Power Plants and High Dams. Therefore, to find the seismic risk for any site, one has to depend upon the data on historical earthquakes. Historical data are available either as the isoseismal maps of the earthquakes, or in the form of lists of earthquakes giving the time of occurrence, epicentral location, magnitude and/or epicentral intensity. To find the expected strong motion ground amplitudes at some site of interest, one has to use the empirical correlations between ground motion amplitudes and magnitude or intensity of the earthquake, developed for other parts of the world. Without precise knowledge of regional attenuation effects of source to site path, it is not possible to estimate the ground motion amplitudes with high reliability, by using earthquake magnitude data. To use the Intensity data as a basis for risk analysis, one needs to know the way in which epicentral intensity decays with the distance. This can be found easily from the isoseismal maps of the past earthquakes.

In this paper, following a procedure similar to that by Anderson (1978), a probabilistic intensity attenuation model has been developed for the earthquakes in Northern India. This model is able to provide the

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probability that an intensity $I_1 (I_1 < I_0)$ will be observed at an epicentral intensity I_0 This information is then applied to develop a model for the analysis of engineering seismic risk at any site in Northern India.

The risk model proposed in this study has been developed on the basis of many previous studies (e. g. Cornell, 1968; De Capua and Liu, 1974; Der-Kiureghian and Ang, 1975; Algermissen and Perkins, 1976; Basu and Nigam, 1977; and Goswami and Sarmah, 1984). This model takes into account the total future seismicities expected in all the potential earthquake sources in the region around the site of interest. The ground motion amplitudes are determined from the total effect of all these sources. Thus, no assumption needs be made regarding the spatial occurrence of the earthquakes, and the seismicity is treated as it actually occurs. Further, the present model is also capable of providing the 'Uniform Risk Spectra' at the site of interest (Anderson and Trifunac, 1978; Anderson, 1979; and Gupta and Ramakrishna, 1985); i. e., the spectra which have the same probability of exceedance at every frequency.

INTENSITY ATTENUATION MODEL

If one looks at the intensity contours in the isoseismal map of an earthquake, it will be seen that the isoseisms, in general, have quite irregular shapes. An intensity value may be observed over a large range of distances from the epicenter in different azimuthal directions. Howell and Schultz (1975) have pointed out that this scatter in the distances for various intensities is very significant. However, most of the studies on intensity attenuation with distance (e.g. Gupta and Nuttli, 1976; Chandra, 1979, 1982; Sergio, 1980 etc.) deal with only the mean behaviour and do not include the wide scatter of the distances for a given intensity level.

It has been shown by Anderson (1978) that for a particular epicentral intensity I_0, log R satisfies a Gaussian distribution; where R represents the epicentral distances to any selected isoseism I_1, in various azimuthal directions. Thus, the probability that the intensity I_1 will be observed at an epicentral distance less than or equal to R, is given by

$$P(R) = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{\log R} \exp\left[-\frac{1}{2}\left(\frac{\mu - x}{\sigma}\right)^2\right] dx \qquad (1)$$

In this expression, μ is the mean and σ the standard deviation of log R. Since the intensity decreases with increase in epicentral distance, probability P, given by equation (1), is also equal to the probability, $P(I \leq I_1)$, i.e., the observed intensity at epicentral distance R is less than or equal to I_1 for an earthquake with epicentral intensity I_o. Hence the probability of observing an intensity value I_1 at distance R is given by

$$P\{I = I_1\} = P\{I \leq I_1\} - P\{I \leq (I_1 - 1)\} \tag{2}$$

To find the parameters μ and σ to be used in equation (1), isoseismal maps of the earthquakes listed in Table 1 have been used. These maps are available in the atlas of Kaila and Sarkar (1978). For each of the isoseismal maps, 36 radii were drawn from the center of the region of highest intensity at equal angular separations of 10°. The distances at which these radii intersect each isoseism are measured and the distance from all isoseismals with the same epicentral intensity are grouped together for each intensity level. Then the values of μ and σ are calculated for all available combinations of I_o and I_1. Using these values of the parameters, theoretical distributions of equation (1) have been evaluated. Figures 1(a) and 1(b) show these distributions for I_o=VI and IX, alongwith the observed distributions. Smooth curves represent theoretical and staircase curves represent the observed distributions. To find the goodness of fit between theoretical and observed curves, Kolmogorov-Smirnov test is used at 95 percent confidence level. Maximum differences between the two curves, for various values of R, are normalized by Kolmogorov-Smirnov critical value at 95 percent confidence level, and these are also plotted in figures 1(a) and 1(b). If this normalized value, D(R), at some distance R is greater than one, then at 95 percent confidence level, Gaussian assumption is not valid for that distance. Kolmogorov-Smirnov critical values have been found from the total number of available radii for each combination (I_o, I_1), assuming that all the radii are independent of each other. As there are 36 radii for each isoseismal map, this assumption is not strictly valid, and hence the critical values used to find D(R) are smaller than the actual values. Taking this point into consideration and looking at the results in figures 1(a) and 1(b), it may be inferred that the observed distributions are not much different than the Gaussian curves. Results for other values of I_o have been found to be of the same quality.

An examination of all the values of μ and σ for various I_o's show that even for the same values of $(I_o - I_1)$, μ and σ are slightly different for differenty I_o's.

TABLE – 1

List of Earthquakes used in this study

Sl. No.	Dte	Location Lat (N°)	Long (E°)	I_0	M	Name of the Earthquake
1.	8 July, 1918	24.5	91.0	X	7.6	Srimangal
2.	19 Jan., 1975	32.5	78.4	X	6.8	Kinnaur
3.	4 Apr., 1905	33.0	76.0	X	8.6	Kangra
4.	15 Jan., 1934	26.5	86.5	X	8.4	Bihar-Nepal
5.	31 May, 1935	29.5	66.8	X	7.5	Quetta (Pakistan)
6.	3 July, 1930	25.5	90.0	IX	7.1	Dhubri
7.	21 Oct., 1909	28.7	68.2	IX	7.2	Baluchistan
8.	14 Nov., 1937	37.5	71.5	IX	7 2	Hindukush
9.	1 Feb., 1929	36.5	70.5	IX	7.1	Hindukush
10.	15 April, 1964	21.0	88 5	VIII	5.5	Calcutta
11.	25 Aug., 1931	29 8	67.2	VIII	7.0	Sharigh (Pakistan)
12.	27 Aug., 1931	29.8	67.2	VIII	7.4	Mach (Pakistan)
13.	21 Nov., 1939	36.5	74.0	VIII	6.9	Pamir
14.	27 Aug., 1960	28.6	76.7	VII	6.0	Delhi
15.	6 Nov., 1975	29.5	78 1	VI	4.7	Roorkee
16.	29 Sept., 1906	23.5	88.5	VI	—	Calcutta
17.	8 July, 1975	25.5	92.5	VI	—	Assam
18.	21 May, 1979	30.3	80.3	VI	6.0	Indo-Nepal

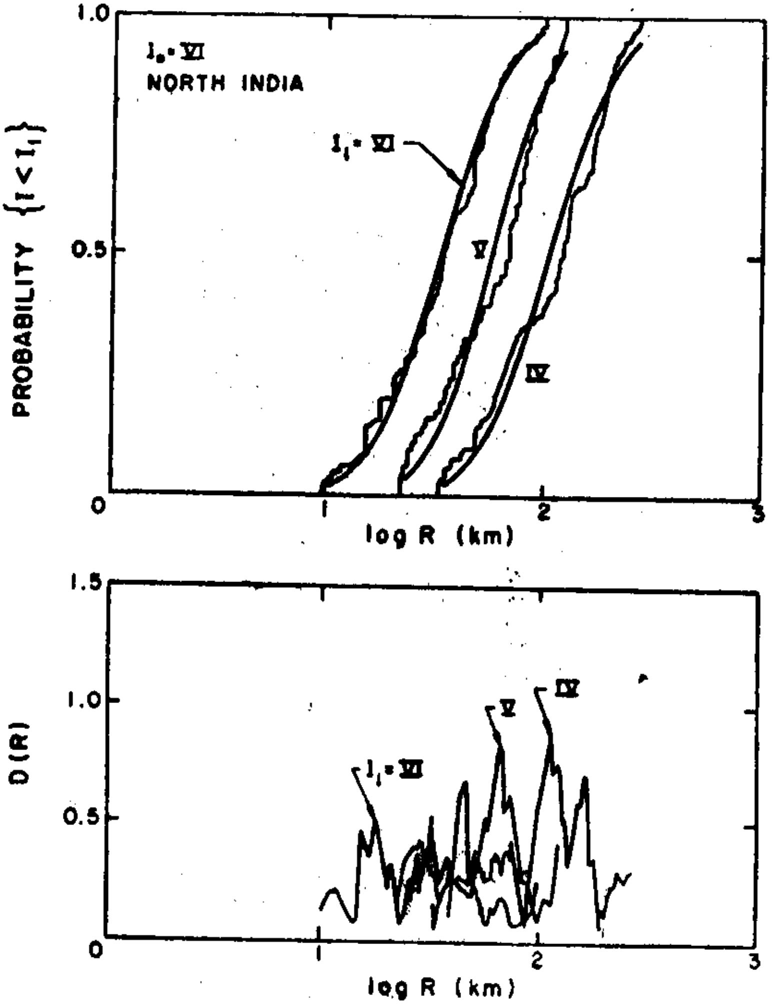

Figure 1 (a)

Figure 1 (a) & (b). Theoretical and observed distributions of log (epicentral distance). The staircase curves in the top figures are determined from the observed data and the smooth curves are the Gaussian approximations to them. Curves for function D (R) in the bottom figures show the differences between the observed and the Gaussian curves in top figures, normalised by Kolmogorov—Smirnov critical values at 95 percent confidence level.

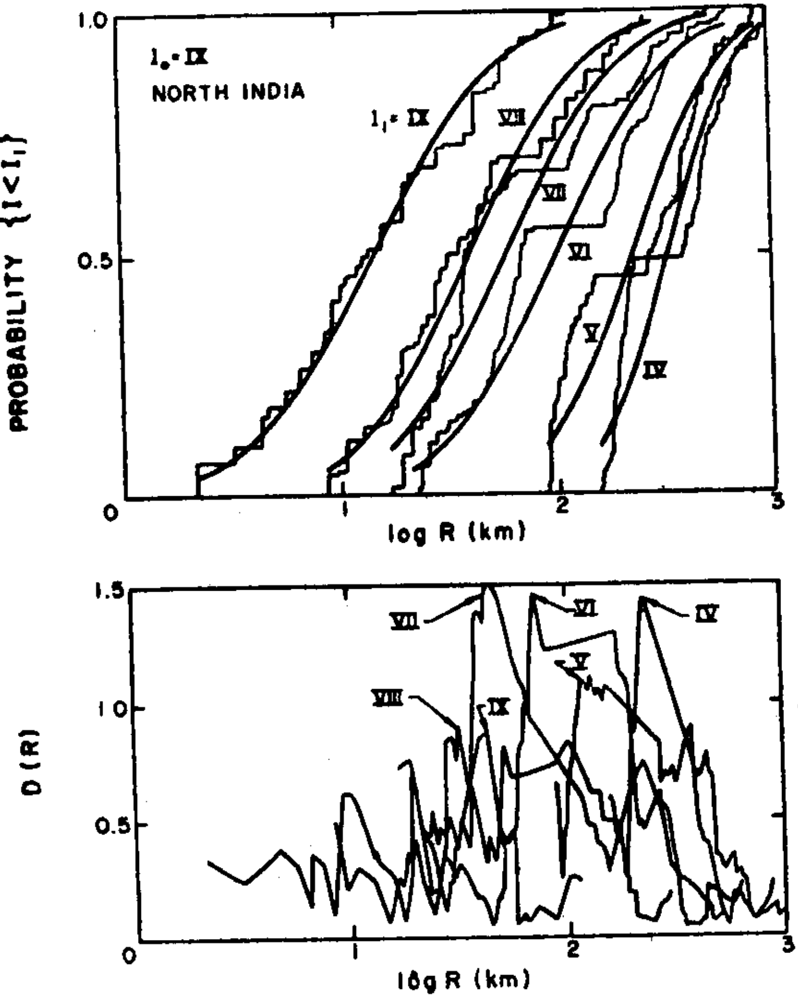

Figure 1 (b)

Therefore, to find the best estimates of μ and σ for different combinations (I_0, I_1), least square regression equations of the following form were fitted to the available mean and mean plus one standard deviation values.

$$(I_0 - I_1) = a \log R + bR + C \tag{3}$$

For mean, μ, and mean plus one standard deviation, $(\mu + \sigma)$, following relations are obtained.

$$(I_0 - I_1) = 1.798 \log R + .0099 R - 2.256 \tag{4}$$

$$(I_0 - I_1) = 2.080 \log R + .0048 R - 3.475 \tag{5}$$

Equations (4) and (5) have been evaluated to obtain the values of log R for $(I_o - I_1) = 0$ to 11. Solutions of equation (4) give the best estimates of μ and the difference between the solutions of equations (5) and (4) are proposed as the best bestimates of σ. These values are given in Table-2. Using the values of μ and σ into equation (1), value of log R can be estimated for any desired probability P $(I \leq I_1)$. Figures 2 (a) and 2 (b) show such results for I_o = IX and X, and for P $(I \leq I_1)$ = .01, .10,. 90, .99 and .50. Observed mean values of log R are also plotted in these figures. It is seen that the theoretical mean curves are in good agreement with the actual mean curves.

TABLE—2

Solutions of Empirical Equations (4) and (5) for log R. Solutions of equation (4) give the mean values μ, and the difference of the solutions of equation (5) and (4) give the values of σ for various values of $(I_o - I_1)$

$(I_o - I_1)$	Solution of equation (4) μ	Solution of equation (5) $(\mu + \sigma)$	Difference
0	1.17206	1.58221	.41015
1	1.59295	1.94725	.35430
2	1.91229	2.23592	.32363
3	2.14549	2.45584	.31035
4	2.31912	2.62459	.30547
5	2.45389	2.75779	.30390
6	2.56209	2.86599	.30390
7	2.65193	2.95642	.30449
8	2.72830	3.03357	.30527
9	2.79451	3.10037	.30586
10	2.85271	3.15955	.30684
11	2.91000	3.21209	.30209

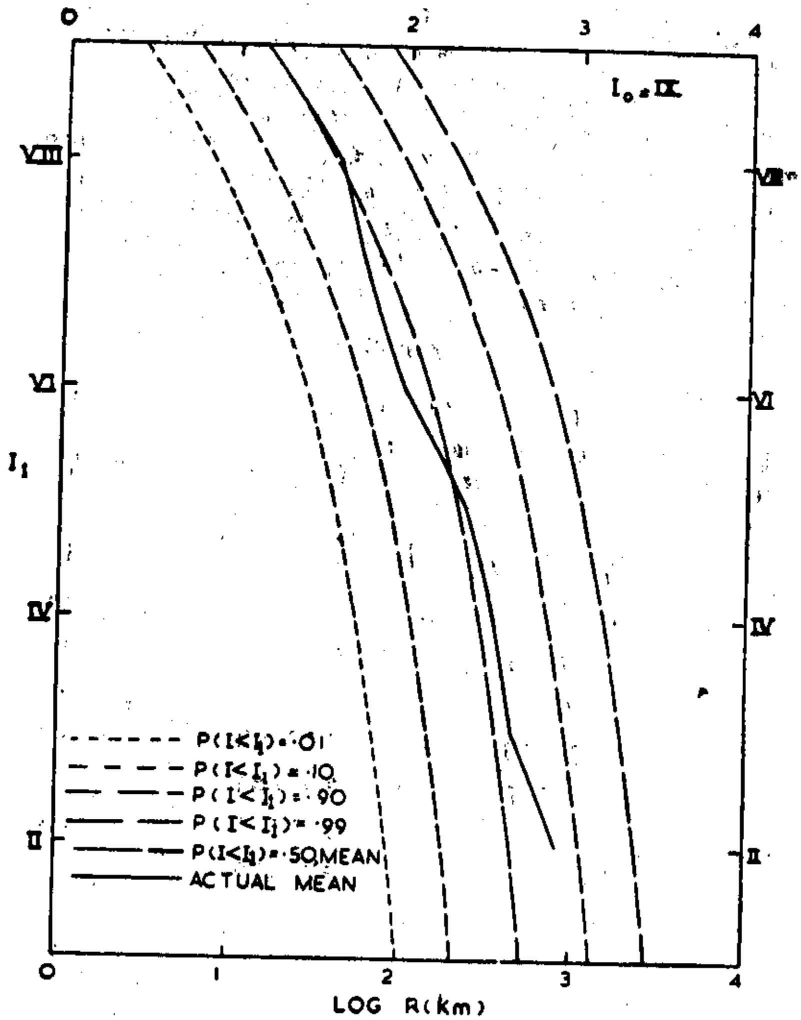

Figure 2 (a)

***Figure 2 (a) & (b).** Intensity Attenuation curves for I_0=IX and X. Continuous curves show the observed mean trend of attenuation, and various dashed curves are for confidence levels of .01, .10, .50, .90, and .99.*

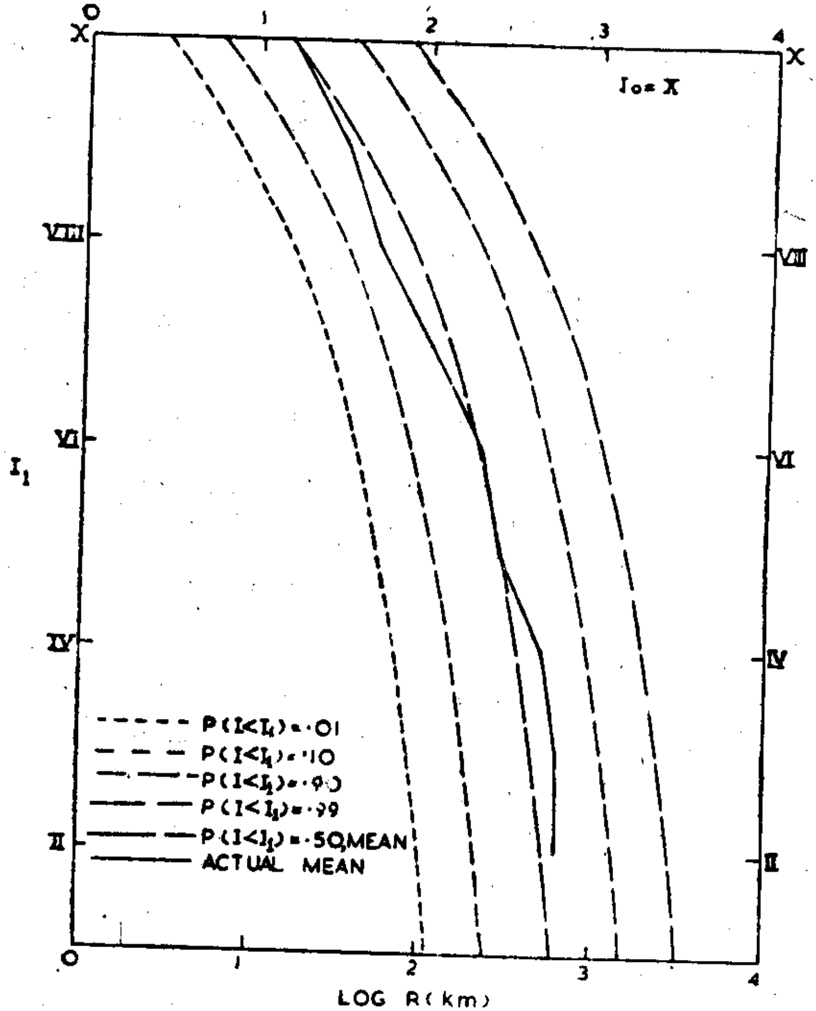

Figure 2 (b)

RISK MODEL

For the purpose of evaluating engineering seismic risk at a project site during the life time of project, one should first define the expected future seismicity of the region around the site. In a region of about 300 km around the project site, all the potential seismic sources should be recognized and the expected number of earthquakes with various epicentral intensities should be assigned to each source. These numbers, $N(I_o)$, for any source zone can be found from the available data on past earthquakes, using the well known relation

$$\log n(I_o) = a + bI_o, \tag{6}$$

where $n(I_o)$ is the annual rate of occurrence of earthquakes with epicentral intensity I_o, and a and b are constants. Thus the numbers, $N(I_o)$, expected in the source zone during D years, the period for which risk is to be estimated, are given by

$$\log N(I_o) = (a + \log D) + bI_o \tag{7}$$

The numbers $N(I_o)$ in a source zone can also be estimated by assuming the available number of earthquakes with epicentral intensity I_o as the mean of a Poissonian Process.

After assigning the numbers $N(I_o)$ to all the sources, each source zone is divided into small elements. Then assuming uniformly distributed seismicity in each zone, the number of earthquakes, $n_i(I_o)$, expected in the ith element during D years can be estimated. If $q_i(I_o)$ gives the probability that certain ground motion amplitude 'A' will be exceeded at the site of interest, due to an event of epicentral intensity I_o in the ith source element; then the probability, p(A), that the amplitude 'A' will not be exceeded due to all the earthquakes of any epicentral intensity in any of the source element, during D years, can be found as described in the following.

Probability that 'A' will not be exceeded due to an earthquake with epicentral intensity I_o in the ith source element $= (1 - q_i(I_o))$

Probability that 'A' will not be exceeded due to k earthquakes with epicentral intensity I_o in the ith element $= (1 - q_i(I_o))^k$.

Probability that 'A' will be exceeded at least once due to the k earthquakes in the above $= 1 - (1 - q_i(I_o))^k$.

Assuming that $n_i(I_o)$ is the mean of a Poissonian distribution (Cornell, 1968), the probability that exactly k events with epicentral intensity I_o will occur in the ith element in D years, is given by

$$\frac{[n_i(I_o)]^k e^{-n_i(I_o)}}{k!} \tag{8}$$

Thus the probability, $P_i(I_o)$, that 'A' will be exceeded at least once in D years due to an event with epicentral intensity I_o in the ith source element is given by

$$P_i(I_o) = \sum_{k=o}^{\infty} \left\{1 - [1 - q_i(I_o)]^k\right\} \frac{[n_i(I_o)]^k}{k!} e^{-n_i(I_o)}$$

$$P_i(I_o)=\left[\sum_{k=o}^{\infty}\frac{[n_i(I_o)]^k}{k!}-\sum_{k=o}^{\infty}\frac{[\{1-q_i(I_o)\}n_i(I_o)]^k}{k!}\right]e^{-n_i(I_o)}$$

$$P_i(I_o)=\left[e^{n_i(I_o)}-e^{[1-q_i(I_o)]n_i(I_o)}\right]e^{-n_i(I_o)}$$

$$P_i(I_o)=1-e^{-q_i(I_o)n_i(I_o)} \qquad (9)$$

Probability that no earthquake with epicentral intensity I_o in the ith source element will cause 'A' to be exceeded = (1 $P_i(I_o)$)

Probability that no earthquake with any epicentral intensity in the ith source element will cause 'A' to be exceeded $=\prod_{I_o=IV}^{XII}(1-P_i(I_o))$

In the above intensities greater than III only are considered because the lower intensities are at the noise level of human perception and their determination is not very reliable Trifunac and Brady (1975) have shown that intensity III corresponds to accelerations of about 5 to 10 cm/sec/sec, which are comparable to the threshold of perception for people. Thus, the probability, p(A), that no earthquake in any source element will cause 'A' to be exceedeo in D years is given by

$$p(A)=\prod_{i=1}^{NE}\prod_{I_o=IV}^{XII}(1-P_i(I_o))$$

Using equation (9), this can be written as

$$p(A)=\prod_{i=1}^{NE}\prod_{I_o=IV}^{XII}e^{-q_i(I_o)\,n_i(I_o)}$$

$$p(A)=\exp\left[-\sum_{=1}^{NE}\sum_{I_o=IV}^{XII}q_i(I_o)n_i(I_o)\right] \qquad (10)$$

In equation (10), NE is the total number of source elements. This expression provides the probability distribution of the ground motion amplitude 'A' expected in D years due to all the earthquakes in all the source zones in the region around the project site. Using this, it is possible to find the ground motion amplitude for any desired confidence level

PROBABILITY FUNCTION $q_i(I_0)$

For evaluating the probability p (A), it is necessary to know the probability function $q_i(I_0)$, which gives the probability that some selected ground motion amplitude will be exceeded at the site of interest, if an earthquake of epicentral intensity I_0 occurs in the ith source element. As observed from the distribution of intensities in figures 1 (a) and 1 (b); in general, at any distance from the epicenter, all the intensities upto I_0 may be observed with some probability of occurrence. However, at a site only one single value of the intensity is to be assigned. Therefore, considering intensities greater than and equal to IV, for the reasons explained before, the probability $q_i(I_0)$ is given by

$$q_i(I_o) = P\{A | I_1 = IV \text{ or } V \text{ or } \ldots\ldots\ldots \text{or } I_o\}$$

$$q_i(I_o) = \frac{P\{A \cap I_1 = IV \cup V \cup \ldots\ldots \cup I_o\}}{P\{I_1 = IV \cup V \cup \ldots\ldots \cup I_o\}}$$

$$q_i(I_o) = \frac{\sum_{I_1=IV}^{I_o} P(A \mid I_1) P(I_1)}{\sum_{I_1=IV}^{I_o} P(I_1)} \qquad (11)$$

In this expression, $P(I_1)$ is the probability of observing an intensity value I_1 at the site due to an earthquake of epicentral intensity I_o in the ith element. This can be found from equation (2). $P(A \mid I_1)$ is the conditional probability that an amplitude 'A' will be exceeded, if an intensity I_1 occurs at the site This can be obtained from the relations between the ground motion amplitudes and the intensity at the site.

Many workers (e.g. Gutenberg and Richter, 1942; Hershberger, 1956; Neumann, 1954; etc.) have attempted to correlate the Modified Mercalli Intensity with the peak ground motion amplitudes. However, these studies have considered only the mean values of the peak ground motions, and thus neglected the large standard deviations about the mean. Trifunac (1976) has taken the standard deviations into account by presenting an empirical relation of the following form between the ground motion amplitudes and the intensity,

$$\log A = ap + bI + c + ds + ev + fI^2 \qquad (12)$$

In this expression, A is the peak ground motion amplitude, which has a probability 'p' of not being exceeded due to an intensity I at the site. Parameter s represents the site condition (s=o for alluvium, s=1 for intermediate rock sites, and s=2 for basement rock sites), v is the component of motion (v=o for horizontal and v=1 for vertical motion).

In equation (12), parameter I takes numerical values from 4 to 12, corresponding to the levels of the intensity IV to XII. Using this equation, the probability $P(A \mid I)$ can be found, which is equal to (1-p). Coefficients a, b, c, etc. in equation (12) have been evaluated by Trifunac (1976) from least square regression analysis, using the data from Western U. S., for the cases of the peak acceleration, the peak velocity, and the peak displacement of the ground motion.

Trifunac (1979) has also derived relations of the form of equation (12) when A represents the Fourier Spectrum Amplitudes, FS(T), at various periods T,

$$\log(FS(T)) = a(T)P_1 + b(T)I + C(T) + d(T)s + e(T)V \qquad (13)$$

In this equation, P_1 is a parameter related to the probability, Pa, of not exceedance of the amplitude FS(T), and it is given by (Anderson and Trifunac, 1977).

$$P_a = \frac{1}{\sqrt{2\pi}\,\sigma(T)} \int_{-\infty}^{P_1} \exp\left[-\frac{1}{2}\left(\frac{x-\mu(T)}{\sigma(T)}\right)^2\right]dx \qquad (14)$$

Coefficients a(T), b(T), etc. and the parameters $\mu(T)$ and $\sigma(T)$ are given by Trifunac (1979) at eleven periods between .04 and 7.5 secs. The probability $P(FS(T) \mid I)$ is equal to (1-Pa), which can be calculated from equations (13) and (14). By evaluating the Fourier Amplitudes FS(T) at every period with the same probability of exceedance, it is possible to find the 'Uniform Risk Fourier Spectrum' for a site. Using the relations between Pseudo Relative Velocity Spectrum amplitudes 'PSV(T)' and the intensity (Trifunac and Lee, 1979), one can also find the 'Uniform Risk Response Spectra'.

DISCUSSION

Modified Mercalli Intensity is a subjective measure of the response of an earthquake on man, structures, and their surroundings (Wood and Neumann, 1931). Due to this subjective and qualitative nature of measuring the level of shaking at a site in terms of intensity, it is not possible to correlate the intensity to the measured ground motion amplitudes. Nevertheless, in the absence of instrumentally recorded strong motion data, intensity observations can provide a basis to study the attenuation characteristics of the ground motion. Further, due to the probabilistic nature of the intensity attenuation model presented in this paper, randomness and the uncertainties in the use of intensity can be taken into account. Another advantage of using the intensity for evaluating seismic risk is that the intensity data are available even for the earthquakes for which instrumental data are not available. (Because the intensity values can be assigned from the description of the damage caused by an earthquake). Furthermore, the correlation between site intensity and the measured ground motion amplitudes does not depend on the source to site path. Hence, one can have better confidence in using such correlations derived for other parts of the world, because the site intensity, which is defined from the observed damages due to an earthquake, has the same meaning at every place.

CONCLUSIONS

Though the Modified Mercalli Intensity has no clear and unique physical meaning for relating it to the recorded strong ground motion amplitudes, it can be used as a basis for risk analysis by the probabilistic approach suggested in this paper. Various uncertainties and lack of knowledge about the physical parameters used in the formulation are accounted by their probabilistic descriptions. When no other better information is available for the risk analysis, the model presented here would be of great use to estimate the ground motion amplitudes with any desired level of confidence. Further, this model is also capable of providing the 'Uniform Risk Fourier and Response Spectra'.

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REFERENCES

1. Algermissen, S.T. and D.M. Perkins (1976), "A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous United States," United States Department of Interior Geological Survey, Open File Report 76-416.

2. Anderson, J.G. (1978), "On the Attenuation of Modified Mercalli Intensity with Distance in the United States," Bull. Seism. Soc. Am., Vol. 68, 1147-1179.

3. Anderson, J G. and M.D Trifunac (1978), "Uniform Risk Functionals

for Characterization of Strong Earthquake Ground Motion," Bull. Seism. Soc. Am., Vol. 68, 205-218.

4. Anderson, J G. (1979), "Uniform Risk Fourier Amplitude Spectra Derived from Intensity Data on Earthquake Occurrence," NUREG/CR=0669, E1 – E27.

5. Basu, S. and N.C. Nigam (1977), "Seismic Risk Analysis of Indian Peninsula," Proc., 6th WCEE, New Delhi India, Vol. I, 782-790.

6. Chandra, U (1979), "Attenuation of Intensities in the United States," Bull. Seism. Soc. Am, Vol. 69, 2003-2024.

7. Chandra, U. (1982), "Attenuation of Strong Ground Motion in India and Neighbouring Regions," VII Symp. Earthq. Eng., Univ. of Roorkee, India, Nov. 10-12, 1982, Vol. 1, 69-76.

8. Cornell, C.A. (1968), "Engineering Seismic Risk Analysis," Bull.Seism. Soc. Am., Vol. 58, 1583-1606.

9. De-Capua, N.J. and S.C. Liu (1974), "Statistical Analysis of Seismic Environment in New York State," V. Symp. Earthq, Eng., Univ. of Roorkee, India, Nov. 9-11, 1974, Vol. I, 389-396.

10 Der-Kiureghian, A. and A.H.S. Ang (1975), "A Line Source Model for Seismic Risk Analysis," Univ. of Illinois, Urabana, U.S.A.

11. Goswami, H.C. and S.K. Sarmah (1984), "An Estimate of Seismic Risk in the Northeast Indian Region," Proc. 8th WCEE, San Francisco, California, U.S A. Vol. I, 125-131.

12. Gutenberg, B and C.F. Richter (1942), "Earthquake Magnitude, Intensity, Energy, and Acceleration," Bull. Seism. Soc. Am, Vol. 32, 163-191.

13. Gupta, I.N and O.W. Nuttli (1976), "Spatial Attenuation of Intensities for Central U S. Earthquakes," Bull. Seism. Soc. Am., Vol. 66, 743-751

14. Gupta, I.D. and T.V S Ramakrishna(1985,),"Evaluation of Risk Fourier Spectra for a Site in Assam Seismic Gap, Northeast India", Bull. Indian Soc. Earthq. Technology, Paper No. 234, Vol. 2, 62-72.

15. Hershberger, J. (1956), "A Comparison of Earthquake Accelerations with Intensity Ratings," Bull. Seism. Soc. Am., Vol. 46, 317-320.

16. Howell, B.F. and T.R. Schultz (1975), "Attenuation of Modified Mercalli Intensity with Distance from the Epicenter," Bull. Seism. Soc. Am., Vol 65, 651-665.

17. Kaila K.L. and D. Sarkar (1978), "Atlas of Isoseismal Maps of Major Earthquakes in India, "Geophysical Research Bulletin, Vol.16, 233-267.

18 Neumann, F. (1954), "Earthquake Intensity and Related Ground Motion," Washington Univ. Press. 40 p.

19. Sergio, S. Su (1980), "Attenuation of Intensity with Epicentral Distance in Phillipines," Bull Seism. Soc. Am., Vol. 30, 1287-1291.

20. Trifunac, M.D and A G Brady (1975), "On the Correlation of Seismic Intensity Scales with the Peaks of Recorded Strong Ground Motion," Bull Seism. Soc. Am, Vol. 65, 139-162.

21. Trifunac, M D. (1976), "A Note on the Range of Peak Amplitudes of Recorded Accelerations, Velocities and Displacements with Respect to the Modified Mercalli Intensity Scale,"Earthquake Notes, Vol.47,9-24.

22. Trifunac, M.D. (1979), "Preliminary Empirical Model for Scaling Fourier Amplitude Spectra of Strong Motion Acceleration in terms of Modified Mercalli Intensity and Geologic Site Conditions," Int. J. Earthq. Engr. and Struc. Dyn., Vol. 7, 63-79.

23. Trifunac, M.D. and V.W. Lee (1979), "Dependence of Pseudo Relative Velocity Spectra of Strong Motion Acceleration on the Depth of Sedimentary Deposits," Dept. of Civil Engr., Report No. 79-02, Univ. of Sourthern California, Los Angeles, U.S.A.

24. Wood, H.O. and F. Neumann (1931), "Modified Mercalli Scale of 1981", Bull. Seism. Soc. Am., Vol. 21, 277-283.

APPENDIX-I. NOTATION

The following symbols are used in this paper.

I = Modified Mercalli Intensity.
I_o = Epicentral Intensity.
I_1 = Any Intensity less than or equal to I_o
R = Epicentral distance.

μ = Mean epicentral distance to an isoseism.
σ = Standard deviation of the distances to an isoseism.
$P(I_1)$ = Probability of observing I_1 at some selected R.
$P(I \leq I_1)$ = Probability of observing $I \leq I_1$ at some selected R.
$D(R)$ = Normalised maximum difference between observed and calculated distributions at distance R.
D = Period in years for which risk is estimated.
NE = Total number of source elements in all the source zones.
$n(I_o)$ = No of earthquakes per year of size I_o in a source zone.
$N(I_o)$ = No. of earthquakes of size I_o in a source zone in D years.
$n_i(I_o)$ = No. of earthquakes of size I_o in ith source element in D years.
A = Ground Motion Amplitude at the site of interest.
$q_i(I_o)$ = Probability of not exceedance for A due to an earthquake of size I_o in the ith source element.
$p_i(I_o)$ = Probability that A will be exceeded at least once in D years due to above earthquake.
$p(A)$ = Probability of not exceedance for A due to all the earthquakes in all the source zones in D years.
$P(A \mid I)$ = Probability of exceedance for A due to intensity I at the site.
$FS(T)$ = Fourier Spectrum Amplitude at period T.
s = Site classification parameter.
v = Component of motion.
P = Probability of not exceedance for A.
P_s = Probability of not exceedance for FS(T).

SEISMOLOGICAL NOTES

Earthquakes in and near about India during the period April to June 1984

S. No.	Date	Origin Time (GMT) H. M. S.	Epicentre Lat. °N	Epicentre Long. °E	Region	Depth (Km)	Magnitude MB	Remarks
1	2	3	4	5	6	7	8	9
1.	April 02,84	04 59 21.5 (USGS)	29.79	68.76	Pakistan	33N	5.1	
	02	04 59 20.0 (NDI)	29.6	69.10	—do—	—	6.2	
2.	02	19 05 41.0 (USGS)	13.78	96.16	Andaman Islands region	49	4.7	
3.	08	14 54 44.7 (USGS)	2.61	98.57	Northern Sumatra	11	4.6	
4.	08	21 52 44.2 (USGS)	13.35	92.31	Andaman Islands region	33N	4.6	
5.	10	20 24 52.6 (USGS)	11.83	95.02	—do—	33N	4.7	
6.	11	08 15 29.4 (USGS)	34.69	79.65	Kashmir Tibet border region	46	4.8	
	11	08 15 29.0 (NDI)	32.80	83.0	Tibet	—	—	
7.	11	13 51 11.6 (USGS)	5.67	94.78	Northern Sumatra	91	5.2	
8.	11	19 36 36.2 (USGS)	13.15	95.66	Andaman Islands region	33N	5.1	

1		2	3	4	5	6	7	8	9
9.	April	13	06 21 53.4 (USGS)	11.67	95.06	—do—	33N	5.0	
10.		13	09 50 13.1 (USGS)	11.88	95.02	—do—	33N	5.3	
		13	09 50 01.0 (NDI)	0.90	92.00	Nicobar Islands region	—	5.6	
11.		15	04 56 44.4 (USGS)	31.59	82.26	Tibet	33N	5.0	
		15	04 56 20.0 (NDI)	32.70	84.0	Tibet	33	—	
12.		15	21 49 50.4 (USGS)	29.92	67.79	Pakistan	18	5.0	
		15	21 49 56.5 (NDI)	30.60	69.0	—do—	—	—	
13.		19	02 53 12.8 (USGS)	36.42	70.86	Hindukush regicn	201D	5 6	
		19	02 53 13.0 (NDI)	36.20	70.60	—do—	—	7.1	
14.		21	11 24 44.5 (USGS)	11.34	95.17	Andaman Islands region	49	4.4	
15.		21	21 17 08.4 (USGS)	36.34	69.33	Hindukush region	95	5.1	
16.		22	02 45 58.8 (USGS)	36.32	69.34	—do—	76	5.1	
		22	02 45 55.0 (NDI)	36.0	69.70	—do—	—	6.9	

1		2	3	4	5	6	7	8	9
17.	April	23	21 26 39.2 (USGS)	36.43	70.76	—do—	209D	5.1	
		23	21 26 43.0 (NDI)	35.90	71.90	—do—	—	—	
18.		23	22 29 58.3 (USGS)	22.04	99.15	Burma China border region	17D	5.9	Felt at Chiang Mai, Thailand.
		23	22 29 49.0 (NDI)	22.40	99.39	—do—	33N	5.0	
19.		24	03 34 13.4 (USGS)	22.04	99.39	—do—	33N	5.0	
20.		24	19 53 14.5 (USGS)	36.32	70.83	Hindukush region	153	4.5	
21.		25	14 58 41.5 (USGS)	26.01	95.60	Burma India border region	109D	4.8	
		25	14 58 48.0 (NDI)	25.50	94.0	- do—	—	5.6	
22.		May 06	15 19 11.4 (USGS)	24.22	93.52	—do—	33N	5.7	Felt
		06	16 19 18.0 (NDI)	25.0	92.40	Assam Bangla-desh border	—	6.7	Felt at Shillong India.
23.		07	08 17 52.8 (USGS)	24.80	94.79	—do—	79	4.7	
24.		09	04 11 03.3 (USGS)	20.26	94.35	Burma	65D	5.0	Felt
25.		11	03 13 44.7 (USGS)	39.40	73.81	Tajik Xinjiang border region	33N	4.8	

1	2	3	4	5	6	7	8	9
26.	May 11	11 45 23.1 (USGS)	31.53	72.81	Pakistan	42	5.0	Felt in the Lahore, Sargodha area
	11	11 45 28.0 (NDI)	30.80	72.90	—do—	—	5.9	
27.	13	21 25 09.2 (USGS)	36.95	71.27	Afghanistan USSR border region	196	4.1	
28.	17	07 06 21.5 (USGS)	36.00	68.93	Hindukush region	33N	4.9	
29.	18	04 28 57.2 (USGS)	29.61	81.88	Nepal	33N	5.6	
	18	04 28 58.0 (NDI)	28.70	81.60	Western Nepal	—	5.1	
30.	18	09 59 43.8 (USGS)	36.49	79.08	Southern Xinjiang China	33N	4.8	
31.	19	06 36 25.0 (USGS)	29.24	81.89	Nepal	50	4.7	
	19	06 36 23.0 (NDI)	29.0	82.0	—do—	—	4.8	
32.	21	09 59 07.7 (USGS)	23.66	91.52	India Bangladesh border region	33N	5.3	
	21	09 59 09.0 (NDI)	24.0	91.30	—do—	—	6.7	

1	2	3	4	5	6	7	8	9
33.	May 23	03 14 21.9 (USGS)	32.96	75.80	Kashmir India border region	58D	4.8	
	23	03 14 25.0 (NDI)	31.80	74.70	India Pakistan border	—	5.0	
34.	27	07 58 33.7 (USGS)	4.89	94.26	Off West Coast of Northern Sumatra	33N	4.3	
35.	29	04 36 11.0 (USGS)	3.55	97.18	Northern Sumatra	89	5.7	
36.	30	22 27 25.4 (USGS)	28.86	83 99	Nepal	33N	4.9	
37.	June 02	10 32 18.4 (USGS)	37.40	71.24	Afghanistan USSR border region	107D	5.2	
	02	10 32 20.0 (NDI)	36.20	71.60	Hindukush region	—	7.0	
38.	06	19 26 12.0 (USGS)	0.42	99.85	Northern Sumatra	33N	4.5	
39.	13	13 28 12.1 (USGS)	4.42	94.89	Off West Coast of Northern Sumatra	38	5.0	
40.	14	13 55 03.8 (USGS)	36.95	96.50	Qinghai Province China	33N	5.0	
41.	15	16 06 11.2 (USGS)	19.74	92.81	Bay of Bengal	33N	4.8	

1	2	3	4	5	6	7	8	9
42.	June 16	13 36 50.8 (USGS)	34.56	70.48	Afghanistan	33N	5.0	
43.	16	15 36 43.9 (USGS)	3.35	97.53	Northern Sumatra	170	4.4	
44.	17	07 32 44.8 (USGS)	36.46	70.86	Hindukush region	189D	4.8	
45.	20	21 28 53.7 (USGS)	39.29	72.99	Kirghiz SSR	33N	4.9	
46.	24	23 10 09.5 (USGS)	4.39	94.88	Off West Coast of Northern Sumatra	33N	4.5	