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ON UNCERTAINTIES IN DESIGN BASIS GROUND MOTION PARAMETERS TOR SITES HAVING INADEQUATE DATA

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ABSTRACT

Assessment of earthquake risk and design basis ground motions for a construction site requires knowledge of frequencies and locations of earthquakes, which are likely to affect the site on the one hand and seismic signal attenuation characteristics of the site region on the other. When sites are not supported by adequate earthquake data and the assessment is made by adopting a certain degree of conservatism, it is desirable to relate the estimates of the ground motion parameters to the expected level of seismicity in the region and to estimate the uncertainties associated with the estimates. A procedure to determine bounds on a ground motion parameter for design basis of a site based on the observed maximum historical earthquake intensity has been suggested. The procedure also offers means to investigate the nature of the existing attenuations function in the light of certain constraints dictated by the procedure.

1. INTRODUCTION

The extent of destruction, which can be caused at a site due to an earthquake is dependent on several factors, e.g. size of the earthquake source (its magnitude or intensity), its location with respect to the site (latitude, longitude and depth), source radiation pattern, amplitude and freguency content of the seismic waves, duration of shaking, local site characteristics and type of the structures. Earthquake risk calulations for a site require an estimate of the probability of the site being struck by a destructive seismic disturbance, vibration or rupture. (In this paper the discussion is limited to the elastic vibrations only). This probability depends greatly on the frequencies of occurrence of earthquakes of different magnitudes. However, in regions which have either poor earthquake recording capability or which have not exhibited higher than moderate seismic activity, and are not suited for detailed geological investigations, it is difficult to accurately estimate the frequencies of earthquakes of different magnitudes. Under these circumstances, it becomes difficult to arrive at accurate estimates of the design basis ground motion parameters. It is, then, considered desirable to place bounds on the estimated values of ground motion parameters in terms of the degree of the adopted conservatism. The limited information on historical earthquakes may be one tool which can be utilized to estimate these bounds. The procedure involves estimating thev ariation in the magnitude-frequency relation for the region to

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account for the uncertainties in the levels of earthquake activity in the near future, and calculate ground motion parameters using the bounds on seismicity. Use of this procedure has been illustrated, through an example of a typical site in a moderately active seismic zone, for which earthquake intensity data on historical earthquakes are available.

At present there exists some differences of opinion on the use of peak ground acceleration as the design basis reference. May be that a different parameter would become more acceptable in the near future for this purpose. However, irrespective of which parameter is used to serve as the design basis, the magnitude-frequency uncertainty will always remain unless the gaps in the data are adequately filled, and so will be the uncertainties in the estimated magnitude-frequency relation of future earthquakes.

2. ANALYSIS PROCEDURE

A schematic procedure for estimating design basis ground motion parameters using a probabilistic approach is illustrated in Figure 1. In the analysis, which follows, the case of a floating earthquake population (i.e. earthquakes are equally likely to occur any where in the region under consideration) has been considered. The site is, ideally, located at the centre of a homogenious and isotropic region, for which the ground motion attenuation characteristics are represented by the variation in the area over which specified values of a certain ground motion parameter (peak ground acceleration in the present case) are exceeded for earthquakes of different magnitudes. Further, it is assumed that earthquake occurrence in the region may be expressed in terms of magnitude-frequency relationship (Richter, 1958).

The probability, $P(a)$, of the peak ground acceleration exceeding a certain specified value a at the site during the life time of a structure is calculated by evaluating the integral:

$$P(a) = \int_{M=M_0}^{M=M_{max}} \int_{S=a}^{S=S_{max}} P_1(M)\, P_2(S)\, dM\, dS \qquad \ldots(1)$$

Here $P_1(M)$ is the probability that an earthquake of magnitude M occurs in the region during the life time of the structure and $P_2(S)$ is the probability that the corresponding peak ground acceleration at the site exceeds the value S. The exceedance probability is converted to the return period of the event, which produces the peak ground acceleration exceeding the value a, through the relation:

$$T = -\frac{L}{\log_e (1.0-P(a))} \qquad \ldots(2)$$

where T is the return period and L is the life time of the structure in years (see Lomnitz, 1976).

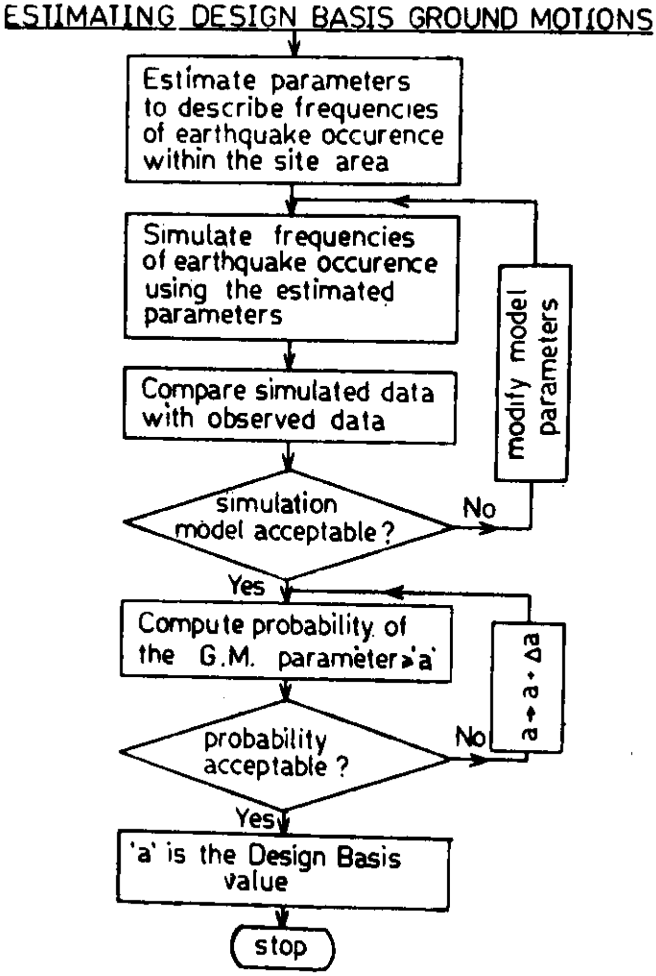

Figure 1. A schematic procedure for estimating design basis ground motion parameters using a probabilistic approach.

Evaluation of this intergral requires an accurate knowledge of the frequencies of earthquakes of different magnitudes affecting the site during the life time of the structure on the one hand and a suitable attenuation function to compute the ground motion at the site on the other. Uncertainties in the knowledge of these two quantities will result in the uncertainties in the estimated values of the peak ground acceleration.

3. FREQUENCIES OF EARTHQUAKE OCCURRENCE

On the basis of global earthquake data between 1904 and 1946, Gutenberg and Richter had proposed a relationship between the frequency of earthquake occurrence and magnitude of the earthquake in the form:

$$N(M) = N(0) \exp(-M/B) \tag{3}$$

where $N(M)$ is the number of earthquakes occurring annually and having magnitudes equal to or greater than M, and B is a constant. This relationship is widely used in estimating the frequencies of earthquakes of different magnitudes to describe global as well as regional seismicity, but in an alternative form, namely:

$$\log N(M) = a - b\,M \tag{4}$$

(Richter, 1958, Kaila and Narain, 1971; Algermission and Perkins, 1976; Bath, 1983). Though this relationship fits reasonably well to the earthquake data in the intermediate magnitude range (say, between 5 and 7), the observed data deviates from this relationship outside this range, particularly at larger magnitudes. It has also been observed that the number of earthquakes in the microearthquake range is not generally as large as that predicted by such a relationship (see Oliver et al., 1966). In actual practice, only a part of the magnitude-frequency relationship may be estimated in the best case of data, which is mostly in the intermediate magnitude range. This is because of poor detectability for small earthquakes ($M < 4$) on the one hand and large recurrence intervals for bigger earthquakes on the other. Frequencies of earthquakes in different ranges, as observed in the period between 1963 and 1980, are given in Table I. These frequencies have been computed from the data in the *NOAA* earthquake data file by actually counting the number of earthquakes in each magnitude range given in the Table. A difficulty which was encountered in this process was the choice of the magnitude scale. It was not always possible to stick to a particular magnitude scale (M_b M_s or M_L) because of the absence of one or the other estimates. We, therefore, scanned all the available estimates, and chose the largest estimate from *MB*, *MS* and *ML* as magnitude of the event. Such a choice may appear to be subjective, but we prererred this in comparison to either eliminating a part of the data or using subjective relationships to convert one type of estimate into another. A regfession analysis on these data shows that the earthquake frequencies in the magnitude 5.0 to 7.5 may be represented by:

$$\log N(M) = 8.3621 - 1.0510\,M \tag{5}$$

whereas those over a larger range of magnitudes (4.5 and above) are better represented:

$$\log N(M) = 5.8780 - 0.2274\,M - 0.0659\,M^2 \tag{6}$$

The main difference between these two expressions (see Figure 2) i.e. (5) and (6) is a smaller number of earthquakes, both at very high and very low magnitudes for equation (6) compared to those for equation (5). There are strong indications in the data that the trend of the log N and M relationship, which is inferred from the data in the intermediate magnitude range, does not extend to the smallest and the largest magnitudes. Use of higher powers of M in the log N–M relationship in seismic risk calculations had also been suggested by earlier authors to deal with the high intensity segment of the linear relationship (Shlien and Toksoz, 1970; Merg and Cornel, 1973).

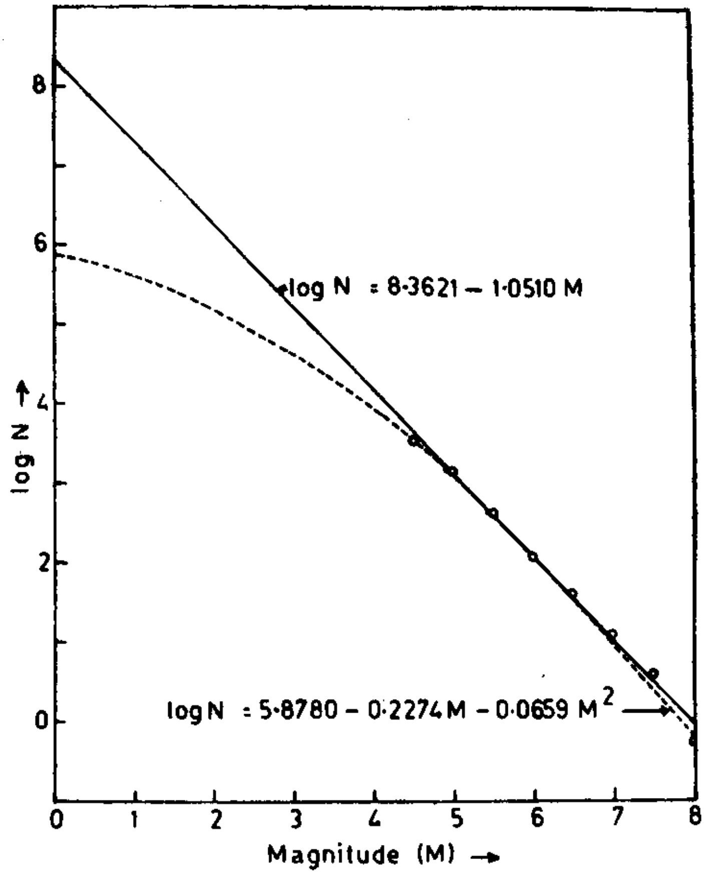

Figure 2. Global Earthquake magnitude-frequency data.

4. REGIONAL MAGNITUDE-FREQUENCY RELATIONSHIP

Unless evidence exists to suggest to the contrary, there is some merit in assuming a similarity between the magnitude-frequency relationships of global and regional data. However, there are significant differences in the rates and extent of seismic energy release in different seismic regions, and adequate data to determine the parameters of the magnitude frequency relationship for a region are not always available. Depending on the availability of the data, one of the following situations may exist:

(a) The region under consideration exhibits an above average seismicity, has a reasonably good network of seismographs to locate most earthquakes above, say, magnitude 3, and hypocentral data for a few decades are well documented. A regression analysis of these data may be carried out to estimate the magnitude frequency relationship.

(b) The region has a well documented history of intensity/magnitudes of large earthquakes of several decades, but data on smaller earthquakes are not of sufficiently good quality to permit a regression analysis for estimating the magnitude-frequency relationship. Extreme event analysis procedures may be adopted to estimate the regression coefficients using the largest earthquake magnitudes. (Gumbel, 1958; Lomnitz, 1976).

(c) There is evidence that earthquakes of magnitude 5 or greater have occurred in the past. Also, sporadic seismicity is observed in the region. No systematic documentation of historical or instrumental data is available. Depending on the extent of the information available from historical data or geological investigations, a magnitude frequency relation may be adopted for approximately describing the earthquake frequencies in the region (see Appendix A).

In either of the situations, there is always an uncertainty in the estimated relationship, which will influence the seismic risk calculations. In what follows, we discuss a procedure to deal with these uncertainties in an objective manner. The procedure involves estimating the upper and lower bounds on the magnitude-frequency relationship under limiting conditions, and using these relationships to estimate ground motion parameters.

5. ESTIMATING THE BOUNDS

As per the current state-of-the art it has been accepted that an earthquake occurring farther than 300 kilometers from a site is not expected to be of any engineering consequences. (USNRC, 1980). Equation 6, when normalized to a circular area of 300 km radius may be written as:

$$\text{Log } N(M) = 2.6218 - 0.2274\, M - 0.0659\, M^2 \qquad (7)$$

This equation represents an average seismic zone, which might experience one earthquake of magnitude equal to or greater than 4.8 per year within this area. At intervals of about one hundred years the magnitude of the earthquake may exceed 6.8. For a zone, for which design basis estimates are required to be computed, but adequate data to establish a magnitude frequency relationship are not available, bounds are computed so that the frequencies of future earthquakes of different magnitudes are likely to remain within the bounds. Determination of the bounds assumes that:

(a) The shape of the magnitude-frequency curve in the zone of interest is similar to that of the global magnitude-frequency relationship.

(b) The differences in the frequencies of earthquakes of different magnitudes in the regional data and those of the global data are interpretable in terms of the difference in the maximum earthquake potential of the region over that of the global average (see Appendix A).

(c) The maximum earthquake potential of the region under assessment may be assessed within one MM unit of intensity ($\pm$ 0.7 units of magnitude), on the basis of the available geological and geophysical data.

Three levels of maximum earthquake potential have been considered. These may be considered as the lower bound, the average value and the upper bound on seismicity respectively. The lower bound corresponds to the highest observed intensity during historical earthquakes. The intermediate level (or the average level) is chosen by scaling the highest observed intensity by one MM unit upwards (0.7 units of magnitude), and the upper bound by scaling the same upwards by two MM units. Such scaling up of intensities to allow for a conservatism in the observed seismicity has been chosen in the light of the recommendations of the IAEA(IAEA, 1979), according to which:

> "First the maximum historical earthquake for the region is determined. The S2 level is then defined one or two units of intensity (MSK or MM scale) more than the intensity scale value of the maximum historical earthquake".

Bounds on the magnitude frequency relationship obtained on these postulates for a region of average seismicity (Figure 3) are utilized to estimate values of peak ground acceleration to serve as design basis. Peak ground accelerations, which may be exceeded at a site located in region having ideal ground motion attenuation characteristics (Housner, 1975) versus return periods, of the causative earthquakes for the three different magnitude frequency relationships are plotted in Figure 4. In Figure 4 we see that the peak ground acceleration steadily increases until the return period increases to about 10,000 years. Beyond this value of the return period, the increase in the peak ground acceleration is only marginal. The figure suggests that an event with a 100,000 years return period may conveniently chosen as a low probability event for fixing the design basis ground motion (for the present model). Return periods of this order are generally considered acceptable for design basis events in several countries, where probabilistic approaches of analysis are used (Stevenson, 1979). Thus, on the basis of Figure 4, a figure of 0.4 g may be inferred, as the design basis acceleration for a region which shows average global seismicity. If the seismicity is over-rated compared to the average one by one MM unit for the largest magnitude earthquake, the figure of 0.40 g may be revised to 0.46 g while an under-rating by the same amount will take it down to 0.30 g.

A return period of 100,000 years corresponds to an exceedance probability of 0.001 during the life time of a structure (which may be taken as about 100

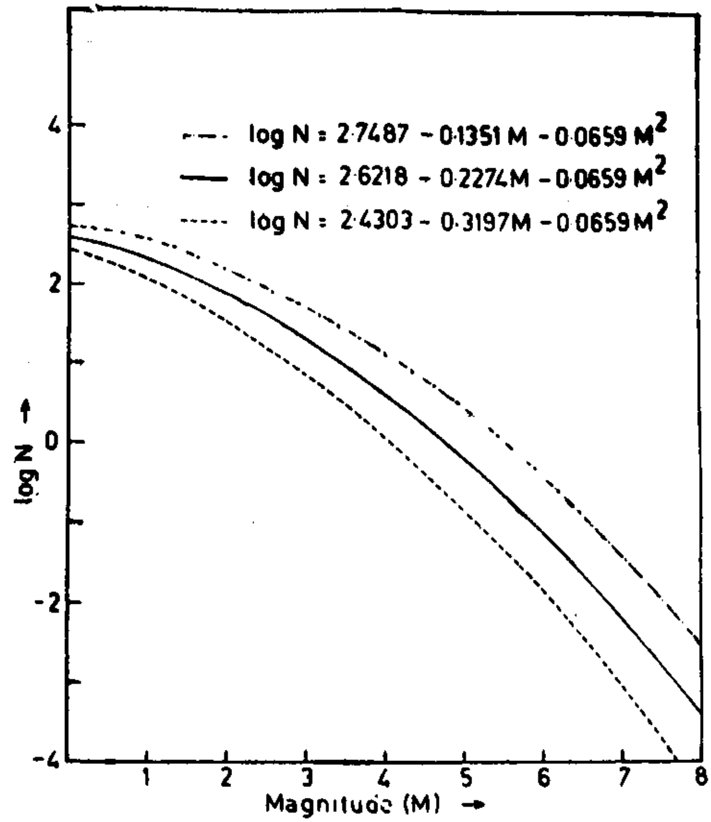

Figure 3. Earthquake Magnitude-frequency relationship for a 300 km radius circular area, based on the average global seismicity. The broken lines are the upper and lower bounds to allow for ± one MM unit difference in the historically observed maximum earthquake intensity (See Appendix-A).

years). Alternatively, with 99.9% probability the peak ground acceleration will remain within 0.38 + 0.08 g for the above model. Further, an over-rating or under-rating of the seismicity so that the largest earthquake in the region goes up or down by one MM unit, will result in an increase or decrease in the estimated value of the design basis acceleration by about 20% of the value at average seismicity.

Discussion

Assessment of seismic risk is largely a matter of scientific and engineering judgement. It is, however, important that the judgement is based on the available information, and in supported by well defined procedures. Further, the degree of conservatism (or the lack of it) should be traceable in the adopted procedures (or in the data), so that the same can be reviewed in the light of the newly available information. It should also be possible to update the

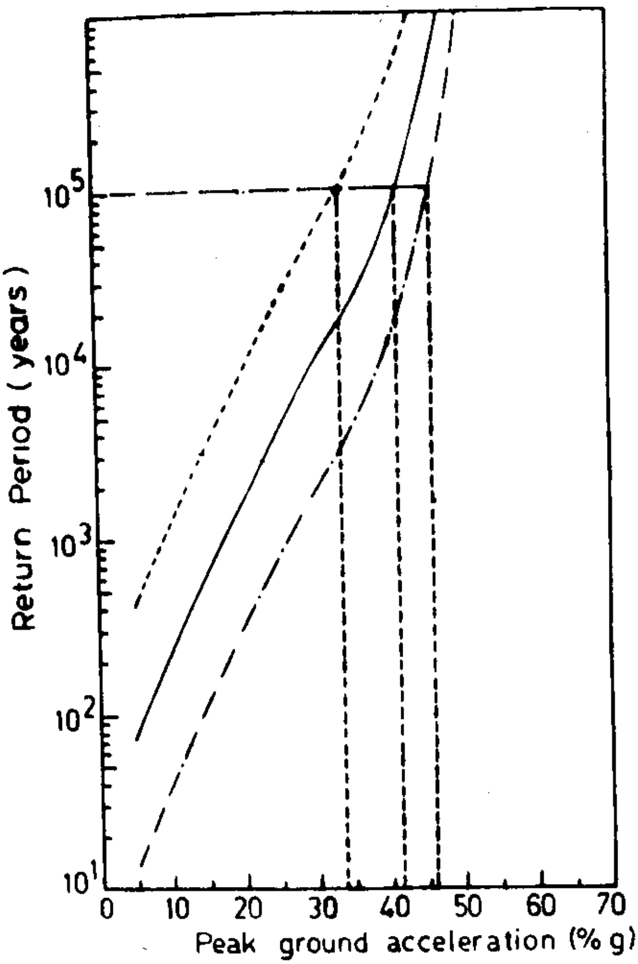

Figure 4. Estimated return periods of peak ground acceleration for a typical site located in an area, whose seismicity is represented by magnitude-frequency relationships of Figure 3 and earthquakes are equally likely to occur any where in the region.

decisions without questioning the very basis of the judgements. For instance, if an earthquake larger than the largest historically documented one, occurs in a region, it should be possible to determine if the seismic risk factor needed revision. The above calculations have suggested means of including newly accumulated information in the evaluation process.

It is, some times, argued that the probabilistic approach of estimating design basis ground motion parameters is not suitable, firstly, because available statistical models are inadequate to describe the earthquake process and, secondly, because it does not lead to "absolutely safe" design. Another objection, which is often raised against this approach is that it is inappropriate to extrapolate the earthquake data (which may at best cover a time interval of a few hundered years) to periods of 10,000 years or more. It should here be noted that the statement that a certain ground motion parameter has a return period of 10,000 years is only a procedure to quantitatively describe the probability of the design basis event. Extrapolation, which is implied in these calculations is only for the next one hundred years or so, i.e. for the expected life time of the structure. After all, the deterministic approach is also based on some assumptions which are made to obtain relationships between the physical parameters of geological structures and earthquakes.

Choice of the shape of the earthquake magnitude-frequency relationship needs special consideration. A linear log N–M relationship determined from the data in the intermediate magnitude range (between 5 and 7 for moderately active areas) is likely to predict a larger number of earthquakes in the micro-earthquake range as well as at larger magnitudes (greater than 7) compared to what is normally observed. If the observed frequencies of microearthquakes are related through such a relationship, derived on the basis of microearthquake data, the frequencies of earthquakes at larger magnitudes (outside the microearthquake range) are likely to be over-estimated, thereby resulting in an over-estimate of risk. The need of exercising care in determining the appropriate magnitude-frequency relationship, therefore, cannot be over emphasized. Scaling the intensities upwards for setting the bounds on the magnitude-frequency relationship is a matter of adding conservatism to the risk estimate, and the scaling factor may be determined from the length of the available data. The scaling factor may be kept lower if the duration of the earthquake data is large enough to include the occurrence of high intensities. The concept of maximum earthquake potential, through its role in describing the seismicity in a quantitative manner, offers a method of including the inadequate historical data in a quantitative manner. Also it allows us to introduce conservatism in an objective approach.

Representation of the attenuation law in the form of ground motion felt areas Vs earthquake magnitude allows us to set limits on the extent of the area from which earthquake information should be included in the calculations. Further, a constraint as the suitability of the attenuation function originates from the requirement that the calculations should lead to an estimate of a design basis parameter whose value can be chosen independent of the return period of the causative event (a low probability event in an absolute sense).

The calculations, which have been presented in this paper, have been carried out in a manner, so that the site specific uncertainties are reduced to a minimum. We have concentrated, mainly, on the role of the magnitude-frequency relationship. A complete knowledge of design basis ground motion parameters, however, requires information on other parameters of ground motion signal, duration of shaking, the role of the site (local geology and soil conditions) in modifying the ground motion and damping of structures, etc. (See Mathiesen et al., 1973; Trifunac and Brady, 1975; Hays, 1980).

Conclusions

1. Uncertainties in the estimates of design basis ground motion parameters for a site may be related to those in the magnitude-frequency relationships of earthquakes in the site region.

2. The observed historical intensities in a moderately seismic region may be utilized to arrive at an approximate magnitude-frequency relationship for a site under consideration.

3. For typical seismic areas showing moderate seismicity and an idealized attenuation pattern, the estimated values of design basis peak ground acceleration for a site, is likely to increase (or decrease) by about 20% with an increase (or decrease) of one MM unit in the maximum earthquake intensity, which can be attributed to that region.

4. The choice of the design basis event should be so decided that the value of the estimated value of the peak ground motion parameter becomes practically independent of the chosen return period of the causative event.

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Discussions with Dr. G.S. Murty on the earthquake magnitude-frequency relationship are gratefully acknowledged. We thank Drs. P. N. Agrawal and H.R. Wasson for providing helpful comments. We have also benefitted from discussions with Mr. V. Ramachandran and Mr. U. S. P. Verma.

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APPENDIX-A

FREQUENCY MAGNITUDE RELATIONSHIP WITH INADEQUATE DATA

We have seen that in the case of global data an expression of the type

$$\log N(M) = a - bM - cM^2 \tag{A.1}$$

represents the frequencies of earthquake occurrence as a function of magnitude. We assume that, unless evidence exists to the contrary a similar relationship is applicable to earthquake frequencies at regional levels. We define the "maximum earthquake potential" of a region as M^* so that the number of earthquakes occurring annually in that region and having magnitudes greater than or equal to M^* is N^* (where N^* is very small). If Mx is the magitude for which equation (A.1) produces N^* earthquakes annually over the same area, then we can write:

$$a - bM_x - cM_x^2 = A - BM^* - CM^{*2} \tag{A.2}$$

where A, B, C are the seismicity parameters for the region under consideration. If we now write

$$M_x = M^* + m \tag{A.3}$$

where m is positive or negative, and assume that m is independent of N^* (i.e. the shape of the $\log N - M$ curve is preserved), we can write using equations (A.2) and (A.3)

$$\left.\begin{aligned} A &= a - bm - cm^2 \\ B &= B + 2cm \\ C &= c \end{aligned}\right\} \tag{A.4}$$

Thus the seismicity parameters A, B, C of one region may be estimated in terms of those of another region, provided the differential in the "maximum earthquake potential", i.e. m may be quantified. The global frequency magnitude relationship with a maximum earthquake potential of, say, 9 may be used to approximately estimate the regional seismicity parameters. Surface expressions of the tectonic structure, historical earthquake data or geological data on ancient earthquakes may be utilized for assigning a maximum earthquake to the region (Chinnery, 1969; Seigh, 1978). It is by no means suggested that the use of the global relationship is the best choice for a comparison standard. Therefore, more accurate estimates of the seismicity parameters are likely to be obtained if a regional frequency magnitude relationship, representing geological and tectonic conditions similar those of the region under consideration, is used.

TABLE I
YEARLY FREQUENCY-MAGNITUDE DATA FOR EARTHQUAKE
BETWEEN 1963 & 1980

Year	Magnitude Range							
	4.5–4.9	5.0–5.4	5.5–5.9	6.0–6.4	6.5–6.9	7.0–7.4	7.5–7.9	> 8
1963	1057	489	183	57	5	1	0	0
1964	1473	777	273	87	19	0	0	1
1965	2040	1123	408	98	56	9	3	0
1966	1699	911	216	56	25	4	2	0
1967	1637	903	236	75	27	1	1	0
1968	1774	974	270	63	15	9	3	0
1969	1698	1026	264	74	26	14	3	1
1970	1631	950	266	80	38	15	5	0
1971	1643	1065	276	78	35	13	6	1
1972	1528	1021	299	85	25	12	3	0
1973	1584	1038	299	65	30	6	7	0
1974	1669	1052	263	69	30	12	2	0
1975	1809	1151	309	71	37	7	7	1
1976	1858	1324	340	82	32	12	3	2
1977	1825	1338	330	71	18	8	3	2
1978	1729	1207	318	68	25	9	7	1
1979	1877	1112	254	71	29	8	5	0
1980	2095	1060	239	73	32	11	2	1
Total:	30626	18521	[illegible]043	1323	504	151	62	10