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Seismicity studies in India

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ABSTRACT. All the available data from historic time has been collected for earthquakes of magnitude 5 and above occurring in and around India and an epicentral map has been prepared.

Earthquake recurrence curve for the Himalayan seismic region and for a few places of special interest, *viz.*, Chatra, Dehra Dun, Delhi and Sonepat have been drawn. It has been found that the slope of the recurrence diagrams is nearly the same in all cases. It does not vary with the change in area or the interval of time taken. The results obtained have been discussed.

1. Introduction

The study of seismicity is of great importance in problems connected with earthquake engineering. Such studies have a special economic significance, for developing countries where large investments are being made in engineering works located in seismic zones. These require an intimate knowledge of the occurrence of earthquakes, their location, frequency, energies and other related parameters. A number of techniques have been proposed in recent years to assess the seismic characteristics of a particular region. St. Amand (1956) made a mathematical approach to define the specific seismicity S and the tectonic flux F. He defined specific seismicity (a name put forward by Ralph Gilman), as the sum of energy released by all earthquakes occurring in an area in a given time divided by the area and time. Mathematically it could be expressed as —

$$S = \frac{K}{AT} \int\limits_A \int\limits_T J \, dA \, dT \qquad (1)$$

where, A is the area chosen, T is the duration of observations, K is a constant depending on the units used and J the energy in ergs. Since the distribution of epicentres is a discrete case, expression (1) may be written as —

$$S_f = \frac{K}{AT} \sum_A \sum_T Ji$$

where Ji is the energy released.

According to Gutenberg and Richter the evaluation of regional seismicity should also take into account the geological field observations of fault phenomenon in addition to the usual study of distribution of earthquakes in space and time from historical and instrumental records. Gutenberg and Richter (1954) also observed that the frequency of earthquake in any region increases rapidly with decreasing magnitude. They showed that —

$$\text{Log}\, N = a - bM,$$

where N is the yearly number of earthquakes in the magnitude range $M \pm \delta M$, M being the magnitude of the earthquake and a and b are constants.

Riznichenko and Nersessov (1961) have proposed that the seismic activity of a place may be defined as the yearly number of earthquakes of a fixed class K of earthquake energy $E = 10^{K \pm 0\cdot 5}$ over an area of 10^4 sq. km. Such studies, because of their economic importance, have attracted the attention of a large number of seismologists throughout the world. Special mention may be made of the works of Riznichenko (1959), Bune (1965) and Oliver, Ryall, Brune, Slemmons (1966). The object of the present paper is to describe some recent studies in seismicity of India on the lines stated above.

2. Earthquake Catalogue and Epicentral Map

Broadly speaking, India can be divided into three main seismic regions. The most active of these comprises of a narrow belt running along the foot hills of the great Himalayan mountains from Kashmir in the west to the hills of Assam and Burma in the east. Parts of the Rann of Kutch and the adjoining areas on the western coast and the Khasi and Garo hills in Assam are also included in this belt. Some of the largest earthquakes in the world have originated from this belt. To the south of this belt, and running almost parallel to it, exists an area of moderate seismicity about 200 miles in width. The rest of the country is comparatively stable and has been free from the ravages of destructive earthquakes. This region of minor seismicity consists mainly of the Deccan plateau.

An idea of the seismicity of the Himalayan belt could be had from the fact, that during the past hundred years, this has been the scene of nearly 40 major earthquakes. Although, earthquakes of this nature must have been occurring in this belt from time immemorial, yet the first scientific study of this subject was undertaken as late as in 1883 by Dr. T. Oldham, the first Director General of the Geological Survey of India. He was also the first to compile a catalogue of Indian earthquakes from the earliest times to the year 1869. Although the catalogue is not exhaustive and contains scattered material, it is perhaps the only handy source from which historical data about Indian earthquakes can be easily obtained.

The first requisite in any seismicity study is the preparation of an up-to-date catalogue of earthquakes containing not only macroseismic data but also information about the location and size of earthquakes. Once a catalogue of this nature is ready, epicentral and zoning maps could be constructed. With this end in view it was decided to compile an up-to-date catalogue of earthquakes occurring in and near India for all earthquakes having magnitudes of 5 or above. Since instrumental data for most of the historical shocks is not available each of the earthquakes already included in the existing catalogues was reassessed, particularly in respect of magnitude and probable epicentre. The main criteria on which the magnitudes were reassessed was the available macroseismic data, the nature and extent of damage near the epicentre, and the distance upto which the shock was felt.

Since the publication of Oldham's catalogue the officers of the Geological Survey of India have been systematically studying the field effects of all important earthquakes of Indian origin but still a considerable number of earthquakes of magnitude above 5 remained uncatalogued. These gaps had to be filled by reference to other sources of information such as *Meteorology in India* (1875-1890). *Monthly Weather Reviews* (1891-1937) of the India Meteorological Department, which contained reports of earthquakes received from various meteorological observatories. The main sources of information have been the following— (1) Report of the British Association for the Advancement of Science, 1911, (2) Seismicity of the Earth by Gutenberg and Richter (1904-1916), (3) I.S.S. (1916-1958), (4) B.C.I.S. (1959—1962), (5) USCGS Epicentre data sheets (1963—1966) and (6) Seismological Bulletins of the India Meteorological Department (1938—1966).

In many cases the magnitude of the shock was not readily available and had, therefore, to be estimated from the distance upto which these were instrumentally recorded. For this purpose all shocks clearly recorded at a distanse greater than 40 degrees but less than 100 degrees were assigned magnitudes between 5—6 and those which were recorded at distances greater than 100 degrees were taken as having magnitudes greater than 6. This criteria corresponds to class 3 and 4 of Pendse's (1948) classification of earthquakes occurring in and near India. The values obtained could be checked with reference to a large number of shocks tabulated in BCIS for which the magnitudes were also available. For some of the latter shocks macroseismic data was also available and provided a further check on the validity of the above criteria. Since the year 1963 earthquakes magnitude are available in the epicentre-cards issued by USCGS. In this way the catalogue has been revised and made up-to-date to the year 1966 for earthquakes of magnitude 5 and above. On the basis of this catalogue an epicentral map was prepared which is given in Fig. 1.

3. Earthquake Zoning map of India

In view of the large scale building activity going on everywhere in the world, the preparation of seismic zoning maps is nowadays regarded as an urgent necessity by all countries. In India the Indian Standards Institution prepared a seismic zoning map (Indian Standards Publication No. IS: 1893-1962) on the basis of (1) Earthquake Epicentres and magnitudes, (2) Maximum past intensity recorded at various places, (3) Broad Tectonic features, such as the existence of known active faults and (4) The local geology.

This map has recently been revised and will be published soon by the Indian Standards Institution in their revised code.

4. Frequency of Earthquakes

In drawing the seismic zoning map of India the frequency of occurrence of earthquakes of different magnitudes in a given region was not taken into consideration due to various reasons. Firstly, the data available was not adequate to draw definite conclusions about frequency distribution in space and time. Secondly the main objective of the zoning map and the entire code of constructional practice was to provide ready information to engineers which could be used for designing ordinary engineering structures. For important structures like large dams, bridges etc special studies have been recommended. It was, however, realised that in order to determine the seismic status of any region the frequency distribution of the earthquakes must be determined. With this end in

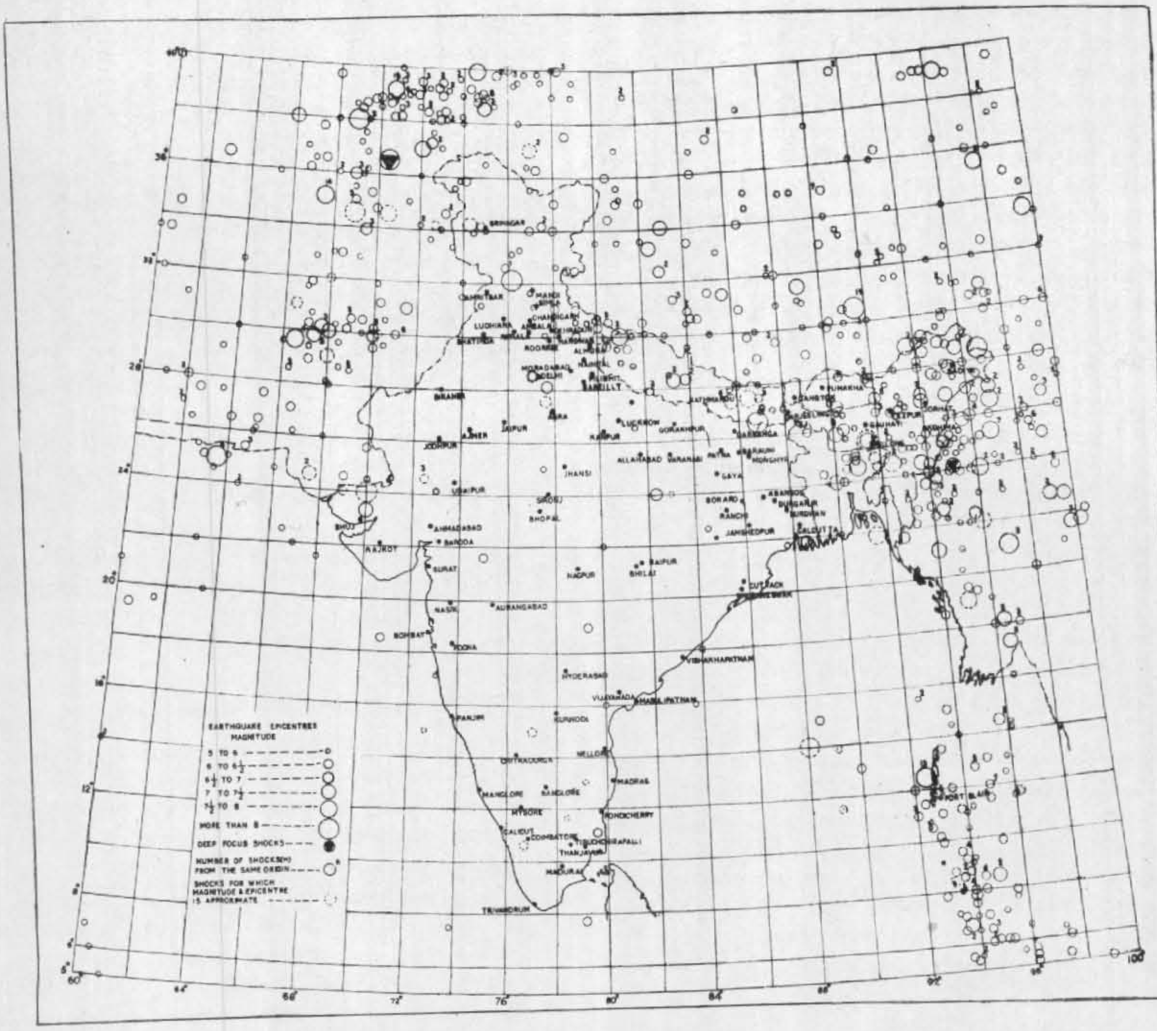

Fig. 1. Map of India showing epicentres

view a tentative study has been made for areas around Chatra and Dehra Dun located at the foot-hills of the Himalayas and Delhi where a large number of minor earthquakes have been experienced during the past few years. Along with these isolated regions a study of the most seismic zone along the Himalayas has also been undertaken with the help of the available data. The observatories at Chatra, Dehra Dun and Delhi are all equipped with sensitive vertical component seismographs and standard W.A. seismographs for determination of magnitudes. Thus magnitudes of all shocks of magnitude 2·5 and above within a radius of 100 km and those of magnitude 3·5 and above within a radius of 250 km could generally be determined.

In a number of shocks it was, however, noticed that although the shock was well recorded by the short period E.M. seismograph yet there was no record on the standard Wood-Anderson seismograph. Since the magnification of E.M. seismographs were not correctly known and the short period associated with the records could not be measured correctly, the magnitudes of such shocks had to be assessed indirectly.

The standard Wood-Anderson seismograph is not capable of producing readable records of magnitude less than 1·5. As the distance increases the minimum readable magnitude also increases. If the shock is located about 100 km away the minimum magnitude should be 2·5 and at a distance of 250 km it should be about 3·5. It is, therefore, obvious that a shock at these distances, if recorded by a sensitive instrument but not by the W.A. should have a magnitude less than the figures given above. Similar threshold can be worked out for other distances. The other limit namely the minimum magnitude shock which could be clearly picked up by a sensitive instrument will depend on the magnification available. After studying a number of records we arrived at the following conclusions. For Chatra and Dehra Dun where the available magnification is of the order of 20,000 all shocks not recorded by W.A. seismographs were classified as follows —

Distance upto which shock has been clearly recorded $\triangle$ (km)	Magnitude (estimated)
0 to $<$ 40	1·5
40 to $<$ 75	2·0
75 to $<$125	2·5
125 to $<$200	3·0
200 to $\leqslant$ 250	3·5

In case of Delhi the available magnification was nearly 40,000 and so a different classification was used.

$\triangle$ (km)	Magnitude
0 to $<$ 40	1·5
40 to $<$ 75	2·0
75 to $<$150	2·5
150 to $\leqslant$250	3·0

Shocks which were felt upto a distance of 15 km were assigned a magnitude of 2·5 and those felt beyond it were assigned a magnitude 3·0 when no other instrumental records were available.

In order to determine the frequency of occurrence of earthquakes of different magnitudes we have followed the method used by Gutenberg and Richter (1954). This technique has been applied to small areas by a large number of workers, mention may be made of the work of Riznichenko (1959) and Bune (1965) who have applied this technique to seismic regions in USSR and have confirmed the validity of this law. They have expressed the earthquake recurrence law in the form,

$$\log N = C + \gamma \log E$$

and have also come to the conclusion that γ is practically a universal constant having the value $-0·43\pm·05$. Instead of using magnitudes these authors have used energy and converted it according to the following equation —

$$\log E_{ergs} = 5·8 + 2·4\, m$$

$$\text{or } \log E_{joules} = -1·2 + 2·4\, m$$

where E is energy and m the unified magnitude. In the present studies we have also followed the same method but used magnitude M_L as used by Gutenberg. Unified magnitude m and M_L are connected by the following relation—

$$m = 1·7 + 0·8 M_L - 0·01\, M_L^2$$

$$\log E_{joules} = 2·88 + 1·92\, M_L - 0·024 M_L^2$$

$$\approx 2·88 + 1·92\, M_L$$

the coefficient of M_L^2 being very small.

$$\therefore\ \gamma = \frac{d \log N}{d \log E} = \frac{1}{1·92}\ \frac{d \log N}{d\, M_L}$$

$$\gamma = -\frac{1}{1·92}\, b$$

which enables comparison of the constants γ and b.

In order to establish the frequency energy relationships for places already mentioned above data for all the shocks occurring within 100 and 250 km of the respective places was collected from original records and the magnitudes assigned to different shocks. Table 1 gives the distribution of earthquakes of different magnitudes for different regions considered. Except in the case of shocks occurring around Delhi and those in the Himalayan region the epicentres could not be located. The statistics have been based on the value of distance alone. We shall now discuss the results obtained for these places.

5. Discussions

Himalayan region — It will be seen from the seismic zoning map that the most active seismic zones 4, 5,6 comprise an area running close to the Himalayan foot hills. These are the areas where earthquakes in the past have caused an intensity greater than M.M. VIII and caused loss of life and property. Most of the larger earthquakes originated in this belt. We have, therefore, chosen this area to see if the earthquake recurrence law could be fitted with the past observations. To avoid uncertainties in the location of epicentres, the area mentioned above has been extended by one degree

TABLE 1

Region	Area considered (sq. km)	Period of observation (years)	Total No. of shocks	Number of shocks of magnitude 2·0	2·5	3·0	3·5	4·0	4·5	5·0	5·5	6·0	6·5	7·0	7·5	8·0	8·5
Himalaya	$1 \cdot 4 \times 10^6$	50 (1916-1965)	295								125	113	39	12	4	1	1
	Do.	5 (1962-1966)	49								33	12	4	—	—	—	—
Delhi	196475	4 (1962-1966)	253	—	143	89	12	6	2	1	—	—	—	—	—	—	—
	31416	Do.	288	129	120	23	11	4	1	—	—	—	—	—	—	—	—
Sonepat	475	$2\frac{3}{4}$ (15 Apr 1964-Dec 1966)	83	56	20	5	1	1	—	—	—	—	—	—	—	—	—
Dehra Dun	196475	$4\frac{2}{3}$ (May 1962-Dec 1966)	108				41	31	23	8	3	2	—	—	—	—	—
	31416	Do.	34			15	13	4	2	—	—	—	—	—	—	—	—
Chatra	196475	7 (1960-1966)	490			248	144	57	25	12	3	—	1	—	—	—	—
	31416	Do.	142		91	28	19	3	—	1	—	—	—	—	—	—	—

to the north beyond the international boundary. The total area thus considered is about 1.4×10^6 km^2. Data for all the earthquakes of mag. 5.5 and above which occurred during the past fifty years, have been used to give a good representation of the earthquakes in the magnitude range, 5·5-8·5.

The results are shown in Fig. 3(a). A similar analysis was attempted for earthquakes which occurred in the area during the period 1962 to 1966 to study the effect of varying the size of the sample. It will be seen that the three points corresponding to magnitudes 5·5, 6·0 and 6·5 lie on the same curve.

Delhi — As mentioned earlier the area around Delhi has been experiencing frequent earth tremors during the last four years. Historical data also shows that earthquakes were not un-common in this region in the past; Delhi was affected by damaging earthquakes in 1720, 1803, 1956 and 1960.

To study the earth tremors occurring frequently around Delhi and Sonepat, temporary observatories were opened at Sonepat and Rohtak about 40 and 65 km respectively away from the main observatory at Delhi. This enabled location of most of minor shocks. The main observatory at Delhi is equipped with sensitive seismographs supplied by USC & GS. For purposes of this study we have drawn three recurrence curves for all shocks, occurring within a radius of (1) 250 km, (2) 100 km and (3) bounded by the rectangle having an area of 475 sq. km as indicated in Fig. 2 which contained most of the local tremors experienced at Sonepat during the last few years. These curves are shown in Fig. 3 and the value of the constants *a*, *b* are given in Table 2. The curves show that a magnitude 6 shock could be expected in the region once in 43 years. This is not improbable as the last earthquake of this magnitude occurred only in 1960. Considering the curves bounded by 100 and 250 km radii around Delhi, it is seen that the former lies above the latter. If the area around Delhi and Sonepat is further reduced as in curve 3 of Fig. 3(b) we find a further increase in seismicity. All these facts show that the centres of seismic activity lie close to Delhi and Sonepat and the frequency of occurrence of earthquakes is relatively larger.

Dehra Dun — Fig. 3(c) shows the recurrence curves for Dehra Dun separately for seismic events occurring within a radius of 100 and 250 km around the station. It will be seen that the points corresponding to low magnitude shocks fall off below the curves drawn particularly in the case of 250 km radius range. This is apparently due to the comparatively low sensitiveness (available magnification about 20,000) of the short period seismograph operating at the station. It is also interesting to note that the recurrence curves of Dehra Dun show a higher seismicity for the region within 250 km radius of the station compared to that of the region within 100 km radius. This fact is easily understandable since the seismically active region of west Nepal and Kangra fall between 100 and 250 km distance of the observatory. This is contrary to the case of Delhi where the seismicity was higher nearer Delhi than at places between 100 and 250 km,

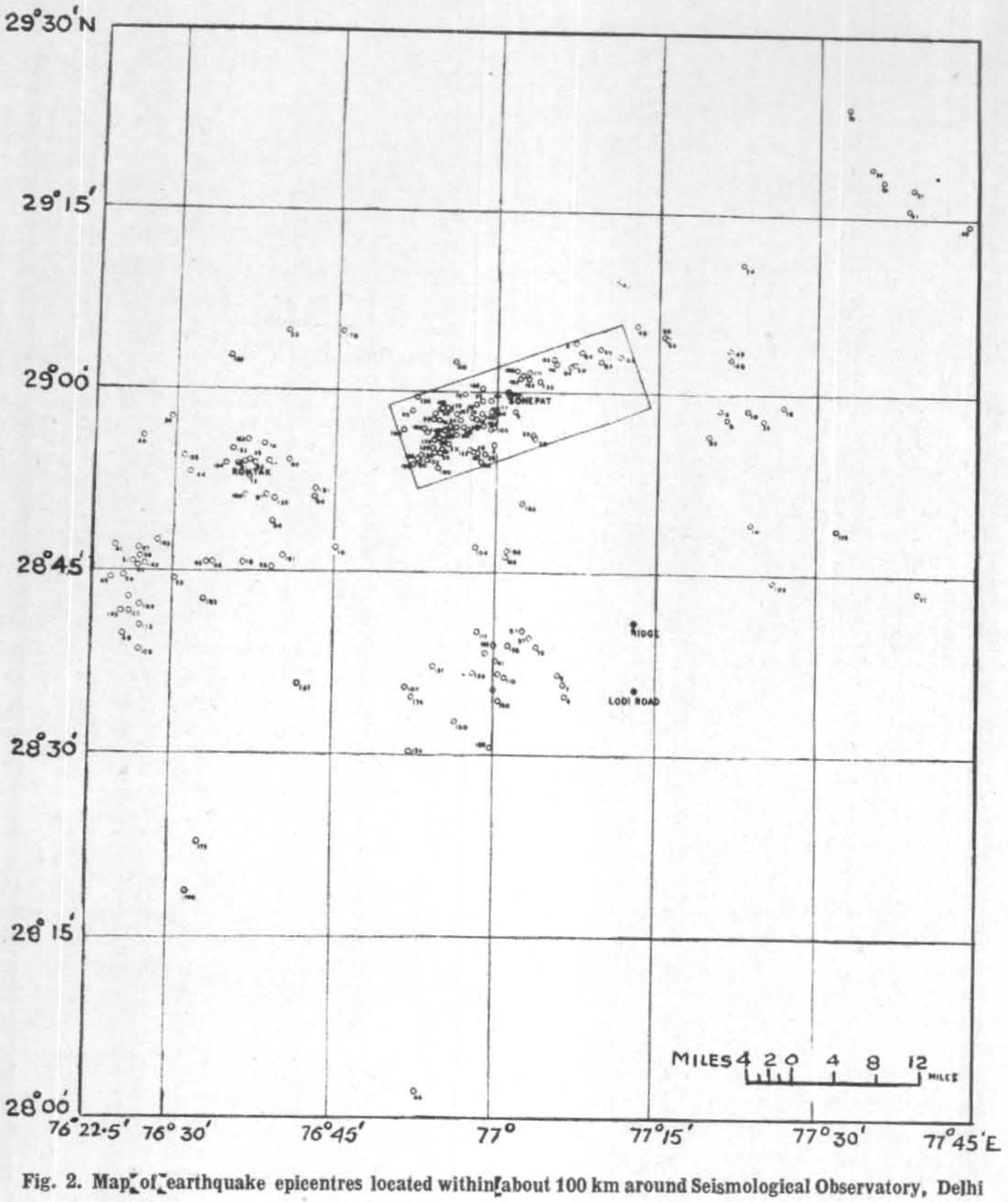

Fig. 2. Map of earthquake epicentres located within about 100 km around Seismological Observatory, Delhi

Period : 15 April 1964—31 December 1966

Chatra — In constructing the recurrence curves for Chatra (Fig. 3d) data for all shocks recorded by a short period Benioff seismograph for the period 1960-66 has been used. The recurrence curves show that the area bounded by 250 km radius around the station is slightly less seismic than Dehra Dun. Here too, the area bounded by 100 km radius has a lower seismicity compared to that of the area bounded by 250 km radius. The high seismicity of the region could be attributed to the cluster of epicentres around Lat. 27·5° N, Long. 86·5°E in the epicentral map (Fig. 1).

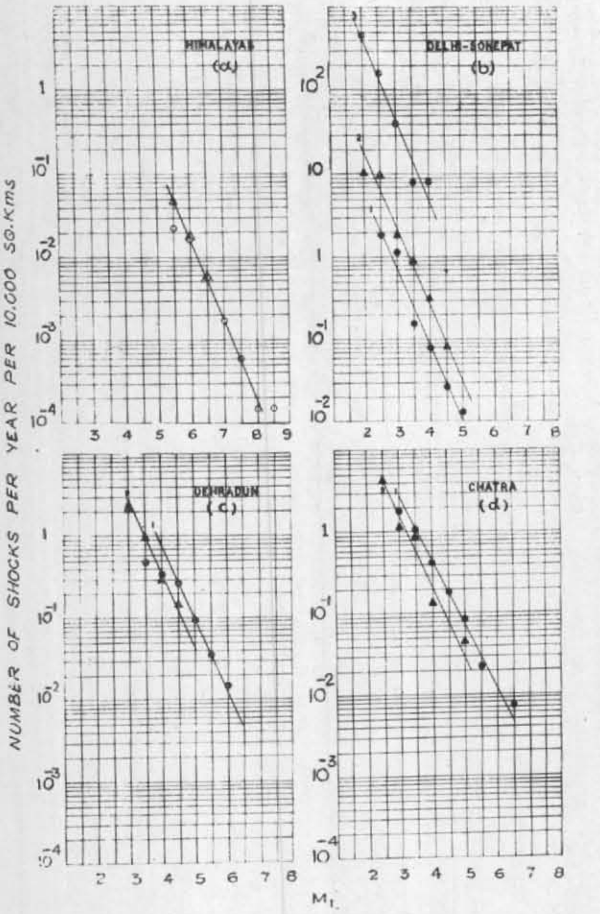

Fig. 3. Earthquake recurrence graph

(a) Himalayan region (b) Delhi—Sonepat

(c) Dehra Dun (d) Chatra

6. Conclusion

Table 2 gives the values of the constants a and b and also the expected time of recurrence of earthquakes of different magnitudes for an area of 10^4 sq. km as well as for the actual area considered. If the epicentre of different magnitudes were evenly distributed, the value of the constant a would have given the relative seismicity of the region. In practice, however, it is seen that in the cases dealt with in this paper this criteria is satisfied to some extent for the Himalayan region as a whole and for the small region considered around Sonepat.

It is interesting to observe that the value of the constant b (the slope of the recurrence curve) is nearly the same in all the cases. It lies between 0·80 to 0·98. This is the case inspite of changing the region, area or the interval of sampling. To this extent these results support the findings of Riznichenko and others that the constant γ is practically universal. The average value of γ from the observations works out to $-0 \cdot 48$ as against the value of $0 \cdot 43 \pm \cdot 05$ found by Riznichenko (1959).

The value of the constant a depends on a number of factors particularly the magnitude interval and the unit chosen for the area. In the present case we have chosen the unit as 10^4 sq. km as previously done by Riznichenko and others. The magnitude interval selected is half-unit which is nearly the same as one unit of scale, *viz.*, one Joule.

The recurrence curves for any region reduced to standard areas (10^4 sq. km in the present case) do not convey a realistic picture of the frequency of earthquakes of various magnitudes in the region. As pointed out earlier this could be so if the epicentres of different magnitudes were uniformly distributed over the region. In order to have realistic picture of the frequency of the occurrence of earthquakes we feel that the area considered should be taken as a whole in which case the figures obtained would give the probability of occurrence of earthquakes of different classes within the area. For this reason we have also tabulated the expected time of recurrence of earthquakes of different magnitudes for different regions.

In considering areas to be chosen for such studies it should be borne in mind that the area should also be tectonically uniform in which case there would be fairly uniform distribution of earthquakes over the entire area. It may be advantageous to consider areas along known active faults for such studies.

A measure of relative seismicity of different places can be obtained by calculating the average early strain release over limited areas around the place to be considered (say 1000 sq. km). The period chosen should be such that it includes at least one largest earthquakes which have ever occurred in the region.

The results obtained seem to indicate that every region is characterised by an earthquake of maximum magnitude, *i.e.*, no earthquake larger than that could occur in the region considered. Unless such maxima are known it would not be advisable to extrapolate the recurrence curves to obtain data for recurrence time for

TABLE 2

Region	Area (sq. km)	a	b	γ	Expected time (yr) for recurrence of earthquakes of following magnitude per 10^4 sq. km					Expected time (yr) for recurrence of earthquakes of following magnitude for actual area considered				
					4·0	5·0	6·0	7·0	8·0	4·0	5·0	6·0	7·0	8·0
Himalaya	$1 \cdot 4 \times 10^6$	4·10	0·98	—0·51	—	—	60	508	5263	—	—	0·44	3·6	37·6
Delhi	196475	2·60	0·92	—0·48	12	100	833	—	—	0·63	5	43	—	—
	31416	3·13	0·92	—0·48	3·8	32	246	—	—	0·8	9·8	78	—	—
Sonepat	475	4·55	0·97	—0·50	0·21	2	—	—	—	4·5	42	—	—	—
Dehra Dun	196475	3·71	0·94	—0·49	1·4	9·0	80	—	—	0·07	0·46	4	—	—
	31416	3·13	0·90	—0·47	2·9	23	186	—	—	0·91	7·3	59	—	—
Chatra	196475	2·87	0·80	—0·42	2·3	14	85	—	—	0·11	0·71	4·3	—	—
	31416	2·76	0·86	—0·45	5	35	250	—	—	1·6	11·2	80	—	—

higher magnitude shocks with the help of data of low magnitude shocks. In all probability the recurrence curves for a region have an upper as well as lower limit, depending upon the tectonic features of the region. It is quite possible that in regions where very large earthquakes occur, the minimum earthquake may also have a larger threshold.

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