Mausam, (1986), **37**, 3, 333-340

550.348.098.64

Study of return periods of earthquakes in some selected Indian and adjoining regions

H. N. SRIVASTAVA and R. S. DATTATRAYAM
Meteorological Office, New Delhi

(*Received 1 September 1982*)

सार — गम्बेल के चरम मान सिद्धान्त का उपयोग करते हुए 5.0 से 8.5 के परिमाण वाले भूकम्पों की पुनरावृति मध्यावधियां अभिकलित की गई हैं तथा छ: क्षेत्रों (1) हिन्दुकुश, (2) कश्मीर और हिमाचल प्रदेश, (3) भारत तथा पश्चिमी नेपाल की सीमा, (4) नेपाल-सिक्किम सीमा, (5) उत्तर पूर्वी भारत तथा (6) अण्डमान द्वीपों के लिए गुटेन्बर्ग रिचटर बारम्बारता परिमाण संबंध द्वारा निर्धारित ऐसी ही मध्यावधियों से इनकी तुलना की गई है। इस उद्देश्य के लिए 1962 से 1976 तक आंकड़ों का एक प्रतिदर्श तथा इससे भी लम्बी अवधि के लिए एक अन्य आंकड़ा प्रतिदर्श का उपयोग किया गया है और इनसे प्राप्त परिणामों की सीमाओं पर विचार विमर्श किया गया है। जब लम्बी अवधि के आंकड़े लिए जाते हैं तो गम्बेल का चरममान सिद्धान्त अधिकतम परिमाण वाले भूकम्पों के प्रत्यागमन काल का बेहतर अनुमान प्रदान करता है। इस प्रकार छ: क्षेत्रों में 8/6 परिमाण वाले भूकम्पों के लिए अनुमानित पुनरावृति मध्यावधियां क्रमश: 22/2, 203/10, 222/11, 160/9, 34/4 और 58/4 वर्ष है।

ABSTRACT. Recurrence intervals for earthquakes of magnitudes from 5.0 to 8.5 have been worked out using Gumbel's extreme value theory and compared with those determined by Gutenberg-Richter's frequency-magnitude relationship for six regions, namely, (A) Hindukush, (B) Kashmir and Himachal Pradesh, (C) India-western Nepal border, (D) Nepal-Sikkim border, (E) Northeast India and (F) Andaman and Nicobar Islands. A data sample for the period 1962 to 1976 and another for a longer period have been used for the purpose and limitations of the results obtained are discussed. Gumbel's extreme value theory gives better estimates of the return period of the maximum magnitude earthquakes when data for longer period is taken. The recurrence intervals thus estimated for earthquakes of magnitude 8/6 for the six regions are 22/2, 203/10, 222/11, 160/9, 34/4 and 58/4 years respectively.

1. Introduction

Assessment of earthquake risk at a given site involves estimation of probability of occurrence of earthquakes of various magnitudes at various distances from the site, identification of source mechanism of earthquakes and the influence of local sub-soil properties on the structures to be designed. A suitable statistical technique is required for assessment of the maximum magnitude of earthquakes based on the past history of earthquake occurrences in different regions.

For this purpose, the catalogue of earthquakes in the region should cover a longer period, be homogeneous, reliable and complete. Catalogue of earthquakes in the Indian region (Tandon and Srivastava 1974) for the last 200 years for earthquakes of magnitude 5 or more based on the data from India Meteorological Department (IMD) is the most reliable amongst the available ones for seismicity studies. Many earthquakes were assigned a range of magnitudes in this catalogue due to the inaccuracies of magnitude determinations prior to 1962. For the sake of amenability to easier mathematical computations, an average value of magnitude has been taken. The magnetic tape file available with the I.M. D. compatable with IBM 360/44 has been updated upto 1976, using all the data available from the *Bulletins of the International Seismological Centre*, UK.

The return periods of earthquakes of different magnitudes in six regions from Hindukush to Andaman and Nicobar Islands have been estimated using Gumbel's extreme value theory. The results have been compared with the return periods estimated using Guntenberg-Richter's frequency-magnitude relationship. The paper also discusses the effects of the limitations of data available for the Indian region.

2. Tectonics of the regions

The Himalayan belt has been divided into the following six regions :

(A) Hindukush	(34° - 38° N, 68° - 72° E)
(B) Kashmir and Himachal Pradesh	(31° - 36° N, 74° - 78° E)
(C) India-western Nepal border	(29° - 31° N, 79° - 82° E)
(D) Nepal - India-Sikkim border	(26° - 29° N, 85° - 89° E)

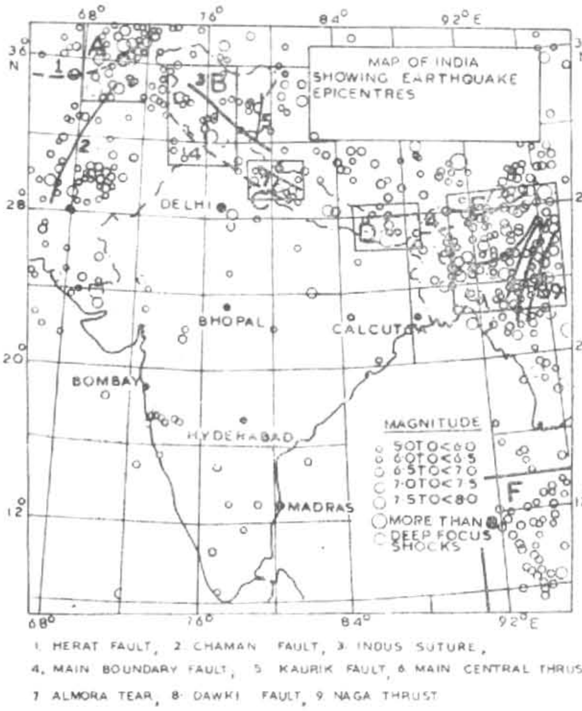

Fig. 1. Epicentral map of Indian sub-continent

(E) Northeast India (23° - 29° N, 90° - 95° E)

(F) Andaman and Nicobar Islands (06° - 14° N, 91° - 96° E)

These are shown in the epicentral map (Fig. 1) of the Indian sub-continent. The above division is based on the following considerations :

(1) Hindukush region has V- shaped lithosphere while Andaman-Nicobar region shows island arc type of plate boundary. Northeast India is characterised by several strong (magnitude $\geqslant 7$) earthquakes with multiple fault systems.

(2) The pattern of energy release is distinctly different for Kashmir-Himachal Pradesh, northeast India and Andaman-Nicobar Islands (Chauhan 1979).

The authors have divided Nepal-India region of central Himalayas into two zones instead of one as taken by Chauhan (1979). This is because the strain release for India-western Nepal border zone is quite different from that for whole region (Srivastava 1973). Similarly, strain release pattern for Hindukush region is distinctly different (Drakopoulos and Srivastava 1970).

(3) In India-western Nepal border region the largest magnitude of earthquake reported so far is 7.5. Great earthquakes of magnitude $\geqslant 8$ have occurred in all the other zones. Due to frequent occurrence of moderate size earthquakes (Tandon and Srivastava 1974) including more recent activity and the development of large number of multipurpose projects more attention has been given to this region.

(4) The epicentral map of India (Fig.1) also shows that there are two distinct clusters of seismic activity located in India-western Nepal and eastern Nepal-Sikkim regions, justifying the division of central Himalayas into two separate zones.

However, the boundaries of the six zones have been chosen in a way that the data can easily be computer processed. Smaller divisions, though more effective cannot be made because seismological data is too meagre for applying statistical techniques. Some details of seismicity are briefly described below :

2.1. *Region A* — In this region earthquakes have been found to occur from a shallow depth of 5 km to 250 km. The largest earthquake in the region of Richter magnitude 8.0 occurred on 21 October 1907 and 7 July 1909. The epicentres form more or less a V-shaped region which are explained by considering the remnants of the lithosphere in the Tethys Oceans. Seismicity is attributed to Herat (north of Kabul) fault, the Chaman fault and mountain ranges in the Pamir knot. Focal mechanism of earthquakes in the region has shown thrust faulting. Tension axis was found to be nearly vertical for earthquakes of focal depth of 200 km, implying the sinking of the lithosphere into the mantle due to its greater density.

2.2. *Region B* — In this region earthquakes occur at depths ranging from 5 to 228 km. The largest earthquake of Richter magnitude 8.0 occurred in Kangra region on 4 April 1905 killing over 20,000 people. Another great earthquake occurred near Srinagar on 30 May 1885 in which 6,000 people lost their lives. The prominent faults in the region are the Himalayan Main

Boundary fault, the Indus Suture Zone and 'Kaurik' tear fault in Himachal Pradesh.

2.3. *Region C* — This is characterised by shallow focus earthquakes with their depth of focus ranging from 5 to 180 km. The largest earthquake in the region occurred on 28 August 1916 in Dharchulla area. Seismic activity is diffused along the Main Central Thrust and on a number of tear faults like Almora and Viakrita thrusts. Focal mechanism of earthquakes also supports thrust faulting (Srivastava 1973).

2.4. *Region D* — This region is also characterised by scattered activity associated with the Main Boundary Fault, the Main Central Thrust and some tear faults identified on landsat imagery. The largest earthquake on 15 January 1934 had a magnitude 8.3. Focal mechanism solutions indicate thrusting but with the predominance of strike slip faulting (Ichikawa *et al.* 1972, Srivastava and Chauhan 1982).

2.5. *Region E* — Earthquakes of shallow to intermediate depth (upto 200 km) characterise this region. The focal depths increase towards Burma along the eastern margin of the Indian plate. The largest earthquake in this region was of magnitude 8.7 which occurred on 12 June 1897. Another big earthquake of magnitude 8.5 occurred on 15 August 1950 in the eastern syntaxial band close to India-Tibet border.

Seismicity of the region is attributed to the Himalayan Main Boundary Fault, the Naga Thrust, the Dawki Fault and a number of other lineaments.

Focal mechanism of earthquakes has shown thrust faulting along the Main Boundary Fault. Strike slip and normal faulting is also indicated showing complexity of the regional tectonics.

2.6. *Region F* — In this region, earthquakes occur from a shallow depth of 5 km to 230 km. The largest earthquake in the region has been reported to be of magnitude 8.1 which occurred on 26 June 1941. The seismic zone is sloping towards east (Srivastava and Chaudhury 1979) from the islands. Eguchi *et al.* (1979) consider that Andaman Sea is not an ordinary subduction related back arc basin, but probably a basin formed by oblique extensional rifting associated with both ridge subduction and deformation back arc area caused by a nearby continental collision. Focal mechanism of many earthquakes in the region indicates predominance of strike slip movement.

3. Methodology

(a) *Gumbel's extreme value theory*

Use of Gumbel's theory (1958) does not require knowledge of the parent distribution. When applied to deal with seismological problems it gives the estimates of the frequency of occurrence of events on the extreme of a statistical distribution and also gives an estimate of recurrence times for these events, provided the following main conditions involved in the development of theory are met :

(1) The conditions prevailing in the past will definitely be valid in the future also,

(2) The observed largest events in a given interval are independent and

(3) The behaviour of the largest earthquake in a given interval in the future will be similar to that of the past.

According to Gumbel (1958), there are three types of asymptotic distributions of extremes, each corresponding to a specific type of behaviour of large values of the variable. In the first type the variable is unlimited and the distribution of the largest values is defined by:

$$H(Y) = \exp\left[-\exp(-Y)\right] \qquad (1)$$

$$Y = C\ (X - U)$$

$$\text{or}\ \ X = U + Y/C \qquad (2)$$

where X is the yearly largest magnitude (in this case the time interval is taken as one year), C and U are parameters and the earthquake magnitude is considered as an independent variable with the cumulative distribution function:

$$F(X) = 1 - \exp(-CX)\ ;\ X \geqslant 0$$

The second type introduces a lower limit and the third type an upper limit for the variable. The following analysis is based on the first type of distribution. The return period (T) of an extreme value equal to or exceeding X is given by:

$$T = \frac{1}{1 - H(Y)}$$

$$= \frac{1}{1 - e^{-e^{-y}}}$$

$$\text{or}\quad Y(T) = -\log_e \log_e \left[\frac{T}{T-1}\right] \qquad (3)$$

where $Y(T)$ is called as the reduced variate for return period T. According to Gumbel (1954), plotting position of the ordered series is defined as:

$$T = (N + 1)/m \qquad (4)$$

where, N is the total years of record and m is the rank of the ordered series. From Eqn. (2) above it is clear that the Gumbel equation is a straight line in X and Y and the parameters can be estimated by least squares method. Substituting the value of T from Eqn. (4) in Eqn. (3) we get:

$$Y = -\log_e \log_e \left[\frac{(N+1)}{(N+1-m)}\right]$$

For a given N, reduced variate can be calculated in advance for all values of m ($m = 1, 2, \ldots\ldots N$). Then from the solutions of minimal equations, the parameters of Gumbel's equation can be calculated. The results are plotted on a specially prepared extremal probability paper which has a double logarithmic abscissae and a linear ordinate. The return periods from the upper scale and the probabilities on the lower scale for a given extreme magnitude may be read from the graph. The

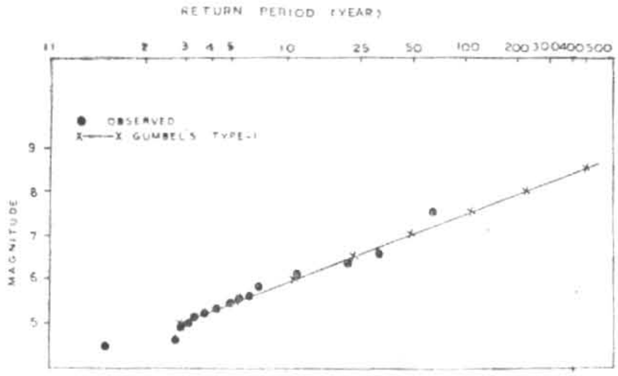

Fig. 2. Gumbel's distribution for region A (Period 1907-1976)

TABLE 1

Return periods for Hindukush region

Magnitude	Gumbel's method 1907-1976 (4.5)						Gumbel's method 1962-1976	Gutenberg-Richter's relationship 1907-1977			Gutenberg-Richter's relationship 1962-1977
	(4.5)	(4.7)	(4.9)	* (4.5)	h≤60km (4.5)	h>60km (4.5)			h>60km	h≤60km	
5.0	1.11	1.09	1.07	1.10	1.61	1.47	1.34	0.25	0.56	1.28	0.12
5.5	1.43	1.39	1.35	1.42	2.55	2.05	2.07	0.54	1.10	2.46	0.39
6.0	2.16	2.11	2.05	2.13	4.44	3.08	3.72	1.16	2.16	4.73	1.29
6.5	3.61	3.58	3.55	3.56	8.13	4.88	7.21	2.50	4.22	9.07	4.29
7.0	6.45	6.53	6.61	6.37	15.33	7.96	14.57	5.37	8.26	17.43	14.20
7.5	11.92	12.34	12.81	11.80	29.34	13.23	30.03	11.56	16.17	33.47	47.06
8.0	22.44	23.79	25.32	22.29	56.62	22.24	62.48	24.85	31.66	64.27	155.91
8.5	42.68	46.31	50.56	42.52	109.70	37.63	130.61	53.43	61.99	123.43	516.55

*converted surface wave magnitudes

TABLE 2

Return periods for (a) Kashmir and Himachal Pradesh, (b) India-western Nepal border and (c) Nepal India-Sikkim border

Magnitude	Region B Gumbel's method 1905-1976	Region B Gumbel's method 1962-1976	Region B G-R method 1905-1977	Region C Gumbel's method 1914-1976	Region C Gumbel's method 1962-1976	Region C G-R method 1914-1977	Region D Gumbel's method 1934-1976	Region D Gumbel's method 1962-1976	Region D G-R method 1934-1977
5.0	2.72	3.09	4.63	2.78	2.51	2.37	2.44	2.92	3.53
5.5	5.15	8.32	8.03	5.34	5.76	4.75	4.49	7.18	5.11
6.0	10.37	24.38	13.94	10.88	14.49	9.53	8.82	19.16	7.39
6.5	21.48	73.54	24.20	22.79	37.80	19.12	17.92	52.71	10.70
7.0	45.14	223.87	42.00	48.41	99.99	38.36	36.96	146.60	15.49
7.5	95.49	683.64	72.90	103.47	265.84	76.96	76.85	409.39	22.43
8.0	202.63	2089.84	126.53	221.83	708.20	154.41	160.39	1144.89	32.47
8.5	430.62	—	219.61	476.25	—	309.81	335.33	—	47.01

results plotted are shown in Fig. 2 for Hindukush region. The continuous line shows the theoretical distribution and the closed circles the observed distribution. The main purpose of this paper is not to test the reliability between the theoretical and the observed distributions, but to obtain an estimate of the return period of earthquakes within the limitations of the data available. Accordingly, emphasis is not made in testing the reliability by plotting the confidence bands of control curves.

(*b*) *Gutenberg-Richter's relationship* — Gutenberg-Richter's frequency-magnitude relationship is given by:

$$\log N = a - bM \quad (5)$$

where N and M represent the number of events for a certain class between magnitudes $M+dM$ and $M-dM$ for a relatively large time interval, 'a' and 'b' are constants. The recurrence intervals obtained from this relation are also given in tables alongwith those obtained from Gumbel's distribution, for all the six regions. a' and 'b' values are also tabulated for all six regions. 'b' values were found to be high (of the order of 1.0), when the data is taken from 1962 onwards. Drakopoulos and Srivastava (1972), Srivastava and Chaudhury (1979), Chatterjee and Dube (1979) also reported 'b' values of the same order. However, low 'b' values were obtained when the data for the whole period was made use of. This difference in 'b' values is attributed to the increased detection threshold after 1962. Although a number of studies for the Indian region have been undertaken relating 'b' to the tectonics of different Himalayan regions, our primary interest in this paper is confined to the estimates of the return periods only.

4. Data analysis

The earthquake data analysed have been taken from the magnetic tape file of I. M. D. A computer programme was developed to pick up the largest magnitude events from each year, which is the basic input for this study. The programme is so framed that it computes the Gumbel parameters and then prints out the return periods for different magnitudes varying from 5.0 to 8.5 in steps of 0.5.

Gumbel's theory requires the data to be continuous over an appreciably long period of time. Since this requirement cannot be fulfilled with the available data for our sub-continent, an alternate procedure suggested by Karnik and Schenkova (1977) has been adopted in the present analysis. According to this, a fictitious magnitude is assigned as the extreme for the 'gap years' depending upon the lowest detection capability of the seismological network. The catalogue prepared by I.M.D. for Indian region includes earthquakes of magnitudes 5 or more and, therefore, the earthquakes during the 'gap years' have a magnitude less than 4.9. This aspect has been studied in detail for Hindukush region (Table 1) where the effect on the return periods using Gumbel's distribution has been studied taking magnitudes as 4.5, 4.7 and 4.9. In this table magnitude assigned for gap years are given in brackets. For all other regions the gap years have been assigned a magnitude value of 4.5. Table 1 also shows the return period estimates for Hindukush region for two different periods, namely, 1907 to 1976 and 1962 to 1976. The detection threshold in the latter period improved to magnitude 4.5 due to the establishment of worldwide standardised seismograph network.

Table 1 also gives the recurrence intervals determined from Gutenberg-Richter's relationship. In Tables 2 and 3 the recurrence intervals for regions B, C, D, E and F are shown for different periods. Depthwise results are also included for regions E and F in Table 3. In Table 4, 'a' and 'b' values computed from Guntenberg-Richter's relationship and 'b' values determined from maximum likelihood method are tabulated for the sake of comparison. In this table figures in the brackets indicate the number of observations used. Full period in this table indicates the same period used for Gumbel's method (Tables 1-3) of analysis. The minimum magnitudes fixed for the 'maximum likelihood method are 4.4, 4.4, 4.6, 4.6, 4.6 and 4.5 for the regions labelled A, B, C, D, E and F respectively depending upon a careful study of detection threshold in different regions. In Table 5, the probabilities that the extreme value is less than or equal to a given magnitude are given for all the six regions for the entire period for which data is available taking the gap magnitude as 4.5.

Prior to the year 1962, surface wave magnitudes were stored on magnetic tape file. From the year 1962 onwards, body wave magnitudes are being stored on magnetic tapes. In order to understand the effect of different magnitudes in data over the recurrence intervals, we have converted the body wave magnitudes (for the period 1962-1976) into surface wave magnitudes by the relation:

$$M_S = 1.08M_b - 0.39$$

Return periods estimated with these modified magnitudes and tabulated for Hindukush region do not show any significant difference (5th column of Table 1).

Since regions A, E and F are characterised by shallow as well as intermediate depth earthquakes, return periods were computed separately for such events.

5. Results and discussion

More data permitting reliable statistical analysis were available for the Hindukush region and, therefore, the corresponding results are likely to be more representative of the true condition. During the period from 1962 to 1976 alone 479 events were recorded in this region which allow greater confidence in the results.

Table 1 shows that the effect of decreasing the period of observations irrespective of data being more uniform or not is to obtain higher estimates of the return periods. Also, the result of increase in the assigned value of fictitious magnitude for the gap years is found to decrease and increase the return period for earthquakes of magnitude less than or equal to 6.5 and greater than 7.0 respectively.

Comparison of recurrence intervals using the Gumbel's estimates with that of Gutenberg-Richter's frequency magnitude relationship shows that the return periods

TABLE 3

Return periods for (a) Northeast India and (b) Andaman and Nicobar Islands

Magnitude	Gumbel's method				Gutenberg–Richter's method		
	1895-1976	$h>40$km 1895-1976	$h<40$km 1895-1976	1962-1976	1895-1977	$h>40$km 1895-1977	$h<40$km 1895-1977
			(a) Northeast India				
5.0	1.65	3.26	1.76	1.82	0.53	3.30	7.22
5.5	2.44	6.71	2.71	3.13	1.14	4.70	12.04
6.0	3.90	14.57	4.46	5.93	2.45	6.86	20.08
6.5	6.50	32.40	7.67	11.77	5.27	9.89	33.41
7.0	11.15	72.85	13.52	23.93	11.33	14.25	55.85
7.5	19.40	164.58	24.15	49.24	24.36	20.54	93.14
8.0	34.07	372.64	43.47	101.89	52.40	29.61	155.34
8.5	60.12	844.52	78.58	211.43	112.68	42.69	259.08
			(b) Andaman-Nicobar Islands				
	1914-1976	1914-1976	1914-1976	1962-1976	1914-1977	1914-1977	1914-1977
5.0	1.31	3.07	1.40	1.60	0.43	1.90	3.91
5.5	2.01	6.13	2.21	3.16	1.01	3.07	11.49
6.0	3.56	12.95	3.97	7.28	2.38	4.96	14.35
6.5	6.86	28.09	7.69	17.92	5.56	8.01	27.48
7.0	13.76	61.65	15.43	45.36	13.02	12.92	52.63
7.5	28.21	136.06	31.56	116.02	30.49	20.86	100.79
8.0	58.42	301.01	65.10	297.98	71.41	33.68	193.03
8.5	121.56	666.66	134.87	766.57	167.21	54.36	369.69

TABLE 4

"a" and "b" values for different regions

Region	Gutenberg Richters relationship								Maximum likelihood method			
	1962-1976		Full period		Full period depthwise				1962-1976	Full period	Full period depthwise	
A		(479)		(250)	$h<60$km	(375)	$h>60$km	(739)	(557)	(770)	$h<60$km (209)	$h>60$km (567)
	7.335	1.04	5.776	0.665	4.58	0.57	5.02	0.584	1.159	0.631	0.406	0.762
B		(52)		(26)					(58)	(75)		
	5.93	0.93	3.593	0.479					1.019	0.631		
C		(44)		(26)					(44)	(56)		
	4.36	0.64	4.456	0.605					0.817	0.596		
D		(27)		(17)					(27)	(40)		
	3.81	0.564	2.703	0.321					0.96	0.61		
E		(99)		(140)	$h\leqslant40$km	(81)	$h>40$km	(174)	(99)	(227)	$h<40$km (67)	$h>40$km (164)
	5.41	0.778	5.52	0.665	3.28	0.44	2.988	0.317	0.968	0.461	0.815	0.38
F		(180)		(117)	$h<40$km	(100)	$h>40$km	(205)	(180)	(267)	$h<40$km (81)	$h>40$km (186)
	6.62	0.96	5.886	0.739	4.04	0.564	3.6	0.416	0.906	0.527	0.82	0.46

TABLE 5

Probability values computed by Gumbel's type-I method for all six regions

Magnitude	Region A $H(Y)$	Region B $H(Y)$	Region C $H(Y)$	Region D $H(Y)$	Region E $H(Y)$	Region F $H(Y)$
5.0	0.0991	0.6324	0.6403	0.5902	0.3939	0.2366
5.5	0.3007	0.8058	0.8127	0.7773	0.5902	0.5025
6.0	0.5370	0.9036	0.9081	0.8866	0.7436	0.7191
6.5	0.7230	0.9535	0.9561	0.9442	0.8462	0.8542
7.0	0.8450	0.9779	0.9793	0.9729	0.9103	0.9273
7.5	0.9160	0.9895	0.9903	0.9870	0.9485	0.9646
8.0	0.9554	0.9951	0.9955	0.9938	0.9707	0.9829
8.5	0.9766	0.9977	0.9979	0.9970	0.9834	0.9918

$H(Y)$ is the probability that an extreme value is less than or equal to X

are generally in good agreement. However, the Gutenberg-Richter's formula systematically underestimates and overestimates the recurrence intervals for lower and higher magnitude levels respectively.

This observation is applicable to regions A, E and F where data is sufficiently large. In regions B, C and D where the data is scanty, no such conclusions could be drawn.

Some interesting results were obtained by separating the events depthwise. In region A, the deeper events of specified magnitudes are more frequent than the shallower ones. On the other hand, the recurrence intervals for regions E and F show that shallower events are more frequent than the deeper ones. This could be due to the difference in the tectonics of Hindukush region as compared to northeast India and Andaman Nicobar Island regions.

The results obtained using Gumbel's extreme value theory are given in Tables 1-3 for the six regions. It may be pointed out that Srivastava *et al.* (1976) have reported much lower estimates for a larger grid, *i.e.*, 30°-40° N, 70°-80° E compared to region B based on the data during the years 1902-1974. The present results may be of greater practical utility for earthquake engineering applications being for smaller region.

The recurrence intervals for region E were worked out for two grids, one bounded by latitude 23°-29° N and longitude 90°-95° E, while the other by latitudes 23°-29°N and longitude 90°-97° E. The latter grid was chosen to include the effect of the great Assam earthquake of 1950 yielding a lower return period estimates of 2.9, 7.4 and 20 years for earthquake magnitudes of 6,7 and 8 respectively. Rao and Rao (1979) have found the return period for the region as 25 years for earthquake of magnitude $\geqslant$ 8.0 for a smaller region bounded by latitude 24.5°-26.5° N and longitude 89.5°-93.5° E based on the data during the years 1926-1971. The results agree with the first grid in the present study when only one earthquake of magnitude 8.5 was included.

The recurrence intervals for earthquakes of magnitude 6, 7 and 8 were found to be 3.6, 13.8 and 58.4 respectively for region F. The difference from earlier reported larger return period of 80 years (Rao and Rao 1979) for 8.0 magnitude earthquake is due to the differences in the periods of observation and the grid size.

It would thus appear that the entire Himalayan region ranging from Hindukush to Nicobar Islands is susceptible to damaging earthquakes of magnitude 6.0 and more with the recurrence interval of 2 to 10 years.

6. Conclusions

The following are the main conclusions of the study :

(1) The recurrence intervals for earthquakes of magnitude 8.0/6.0 using Gumbel's extreme value theory works out as 22/2, 203/10, 222/11, 160/9, 34/4 and 58/4 years for (A) Hindukush, (B) Kashmir and adjoining Himachal Pradesh, (C) Western Nepal-India, (D) Eastern Nepal-India-Sikkim, (E) Northeast India and (F) Andaman-Nicobar Islands regions respectively.

(2) All the Indian earthquakes of magnitude greater than 8 have occurred during the period when the data has been imcomplete. It is from 1962 that somewhat more homogeneous data is available but no major earthquakes have occurred. This obviously leaves lot of scope for improvement in the results when more data will become available particularly for higher magnitude earthquakes.

(3) The differences in earlier results to those reported in the study mainly relate to differences in size of regions and period of data covered otherwise the results given here are (generally) in conformity to those already available.

(4) The 'b' values obtained by using Gutenberg Richter's method are in general higher compared to those obtained by the maximum likelihood method.

References

Chatterjee, S.N. and Dube, R.K., 1979, *Mausam*, **30**, pp. 191-202.

Chauhan, R.K.S., 1979, Some quantitative seismicity studies in north India including Kutch, *Mausam*, **30**, p. 231.

Drakopoulos, J.C. and Srivastava, H. N., 1972, *Ann. Geofisica*, **25**, 593-603.

Eguchi, T., Uyeda, S. and Maki, T., 1979, Seismotectonics and tectonic history of the Andaman Sea, *Tectonophysics*, **57**, 35-51.

Gumbel, E.J., 1958, Columbia Univ. Press, New York.

Ichikava, M., Srivastava, H. N. and Drakopoulos, J., 1972, Focal mechanism of earthquakes occurring in and around Himalayan and Burmese mountain belt, *Papers in Meteorology and Geophysics* (Tokyo), **23**, 149-162.

Karnik, V. and Schenkova, Z., 1977, Proceedings of the symposium on the analysis of seismicity and seismic risk, LIBLICE (17-22 October).

Rao, Sitapati P. and Rao, Ramalingeswara B., 1979, Estimated earthquake probabilities in the northeast India and Andaman-Nicobar Islands, *Mausam*, **30**, 267-273.

Schenkova, D. and Schenk, V., 1975, Return periods of earthquakes and trends of seismic activity, *Pur. Appl. Geophys.*, **113**, 683-693.

Srivastava, H. N., 1973, The crustal seismicity and nature of faulting near India Nepal and Tibet trijunction, *Himalayan Geology*, 381-393.

Srivastava, H.N. and Chaudhury, H.M., 1979, Seismicity and focal mechanism of earthquakes in Andaman Islands, *Mausam*, **30**, 213-230.

Srivastava, V.K. and Chauhan, R.K.S., ..., Study of focal mechanism solutions of earthquake events distributed in and around the Indian lithospheric plate, *Mausam* (Sent for publication).

Srivastava, V. K., Chauhan, R.K.S. and Nigam, Rajiv, 1976, Largest value theory applied to probability of earthquake occurrence, Bull. of the Indian Society of *Earthquake Technology*, **13**, 19-23.

Tandon, A.N. and Srivastava, H. N., 1974, *Earthquake occurrence in India*, Earthquake Engineering, Jaikrishna Volume, Sarita Prakasan, Meerut.