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Long-Term Seismic Hazard Analysis in Northeast Himalaya and Its Adjoining Regions

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Abstract Northeast Himalaya and its adjoining region India, has been delineated into nineteen seismogenic sources on the basis of certain seismological and criteria for the estimation of repeat times of earthquakes, to apply a regional time- and magnitude-predictable model for all these sources to study the future seismic hazard. For this, published earthquake data since 1906 to 2008 from different available earthquake catalogues and books have been used. Considering the inter-event time between successive mainshocks, the following two predictive relations were computed: $logT_t = 0.01\ M_{min} + 0.22\ M_p - 0.05\ log\ m_0 + 0.98$ *and* $M_f = 0.89\ M_{min} – 0.26\ M_p + 0.29\ log\ m_0 - 5$. Multiple correlation coefficient and standard deviation have been calculated as 0.50 and 0.26, respectively for the first relation and 0.75 and 0.41, respectively for the second relation. The positive dependence of T_t on M_p indicates the validity of time predictable model on the area considered in this study.on the basis of these relations and using the magnitude and time of occurrence of the last mainshocks in each seismogenic source, time dependent conditional probabilities of the next mainshocks and their occurrence during the next 10, 20 and 30 years as well as the magnitude of the expected main shocks are forecast.

Keywords recurrence time, inter-event time, time- and magnitude-predictable model, Northeast Himalaya

1. Introduction

An earthquake hazards programme requires chiefly three parameters to evaluate i.e. magnitude, time of occurrence and the location of the epicenter/ focal depth related to an earthquake. Delineating a potential zone and predicting future seismic hazards in a region help taking appropriate measures in such eventuality and necessary mitigation measures to minimize the destructive effects caused by an earthquake. Fore-warning of earthquake related activities in a region help minimize resulting destructions up to some extent and can save lives. Such an action eventually provide an opportunity for taking appropriate measures for future planning and policy making in the potential zone. Several attempts have been made during the last five decades to understand the tectonic processes that cause the earthquakes and their association with the precursory activities that have some causative relationship with forthcoming earthquake ((Mogi, 1969; Evison, 1977; Habermann, 1981; Shanker et al., 1995). These findings have helped developing several new earthquake generation seismicity models (like "time predictable" recurrence model formulated by Shimazaki and Nakata, 1980) and associated precursory phenomena (seismic and non-seismic) that precede large earthquakes. One pre-requisite requirement of seismic hazards prediction is the identification of seismically potential zone in earthquake prone region. But due to the complex structure of Earth's interior, it may be difficult to estimate all the required parameters related to a forthcoming earthquake (location, magnitude and time of occurrence) with reasonably good accurate.

The earthquake recurrence intervals are the time interval between the largest mainshoks occurred in earthquake prone region. This interval may vary from several decades to several hundred years. If a particular pattern were identified associated with seismic activity in the hypocentral zone and its surrounding after the occurrence of one large earthquake to next earthquake, then it will help for long term-prediction of large earthquake in that region. Earlier different models were proposed for the recurrence of earthquake generation in the past. After long debates and discussions a Regional Time- and Magnitude- Predictable Seismicity Model have been accepted and applied successfully in different seismically active regions to estimate the magnitude and the time of occurrence of forthcoming earthquakes. These models have put forward to Central Himalaya and its vicinity (Paudyal *et al*., 2009); Eastern Anatolia (Sayil, 2005); Taiwan (Wang, 2005); Hindukush Pamir Himalaya (Shanker and Papadimitriou, 2004); China (Qin *et al*., 2001); Circum-Pacific belt (Papadimitriou *et al*., 2001); Greece and Japan (Karakaisis, 2000); Alpine-Himalayan belt (Pa-

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pazochos *et al*., 1997); North-east India (Shanker and Singh, 1996); Indonesian region (Papadimitriou and Papazachos, 1994); the Aegean area (Papazachos and Papaioannou, 1993); New Guinea–Bismark sea region (Karakaisis,1993); the Western coast of the South and the Central America (Papadimitriou, 1993); Greece (Papazachos, 1989); North-East India Himalaya (Panthi *et al*., 2011) and others. Applicability of the Time- and Magnitude Predictable model has been tested in northeast India Himalaya and its adjoining regions bounded by 20°-32° N and 88°-98° E, and finally evaluate the seismic hazards in the identified seismogenic sources.

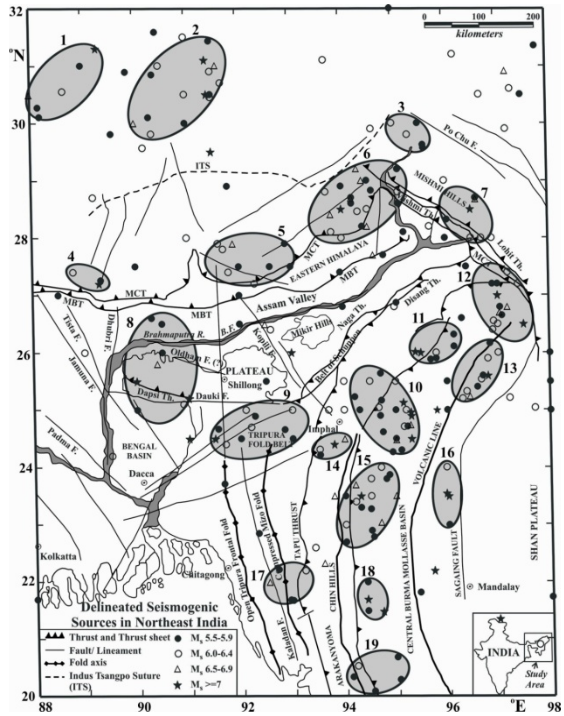

Figure 1. Spatial distribution of earthquake with $M_s \geq 5.5$ occurred during the period 1906-2008 in northeast India Himalaya and its adjoining regions. Using this distribution, 19 seismogenic sources have been delineated in relation to the major tectonic features of the area and are considered to test the validity of Time-and Magnitude Predictable model and to estimate the probability of future seismic hazards in each of the delineated seismogenic sources. The seismogenic sources are enclosed by shaded elliptical areas (Panthi et al., 2011).

2. Earthquake Data and Seismogenic Sources

Data set for the area bounded by 20˚-32˚ N and 88˚-98˚ E has been considered to study the long-term earthquake hazard prediction (Panthi *et al*., 2011). This area covers the Eastern Himalayan belt, adjoining southeastern Tibet and northeast India region including Arakan-yoma fold belt and consists of several mountain peaks, thrust, faults and lineaments. Compilation of the seismicity data base and delineation of the region into seismogenic sources have already been discussed in detail in (Fig 1) (Panthi *et al*., 2011). One of the basic requirements for determination of prediction relations is the values of a, b, M_{max} and log m_0 for each seismogenic source zone Table (1).

This table shows respectively, the region and code number of each seismogenic source zone as shown in Fig. 1. The a-value and b-values are calculated separately for each seismogenic source zones using the method of least square the value of M_{max} is determined with the help of historical and modern dataset for each source.

3. Methodology

The groundwork results obtained in their previous work (Panthi *et al*., 2011) have been used as input data in the present work to extended the work further to determine the seismic hazard in each nineteen seismogenic sources.

The relation of repeat time (T) (between two successive mainshocks) with the magnitude of the preceding mainshock, M_p, is represented in the form of

$$\text{Log } T = c\, M_p + a \tag{1}$$

where c is a constant and it is the gradient of least square best fit line with a positive value, and ‘a ‘is also a constant which is a function of the magnitude. The value of the constants ‘a’ and ‘c’ depend upon the tectonic characteristics of the sources. Equation (1) indicates that the time interval between the two successive mainshocks, in a seismogenic source, is linearly related with the coseismic slip of the previous mainshock. It supports the time-predictable model, which predicts that the inter-event time is proportional to the co-seismic slip of the last main shock (Shimazaki and Nakata, 1980). The variable repeat times (T) estimated among the seismogenic sources are due to the variation in the value of constant ‘a’. For validity of the time-predictable model established for a region, the value of c (the coefficient of Mp) is always positive (Qin *et al*., 1999). The worldwide value of this coefficient has been estimated as 0.33 (Papazachos and Papadimitriou, 1997). Similarly the regional value of ‘c’ for northeast India, Greece, Aegean area, the western coast of the South and the Central America and for Nepal Himalaya is estimated to be as 0.36, 0.32, 0.35, 0.21 and 0.32 respectively.

Later the Equation (1) was modified by adding some parameters which represent the exact nature of the seismogenic sources. The regional time- and magnitude- predictable model of the seismicity proposed by Papazachos (1992) and its modified form by Papazachos and Papaioannou (1993) is represented by the following two relations:

$$\text{Log } T_t = b\, M_{min} + c\, M_p + d\log m_o + q \tag{2}$$

and

$$M_f = B\, M_{min} + C\, M_p + D\log m_o + m \tag{3}$$

where T_t is the inter-event time measured in years, M_{min} is the surface-wave magnitude of the smallest main shock considered, M_p is the magnitude of the preceding main shock, M_f is the magnitude of the following main shock, m_0 is the moment rate in each source per year that expresses the tectonic loading exerted in the volume of each seismogenic region, and q and m are constants. For this purpose, a computer program written by C. Papazachos (personal communication, 1992) was used for the determination of various parameters of the model using the input data generated. Table 2 values of the parameters for each seismogenic source necessary to proceed using these equations.

4. Development of Predictive Regressions

Regression was performed to determine the model parameters (b, c, d, q, B, C, D and m) expressed by relations (2) and (3) using all available data (Table 2). A total of eighty four data sets pertaining to nineteen seismogenic sources of the Northeast India Himalaya and its adjoining regions are used to establish the time and the magnitude predictable relationships as follow:

$$\log T_t = 0.01\ M_{min} + 0.22\ M_p - 0.05 \log m_0 + 0.98 \quad (4)$$

has a correlation coefficient of 0.50 when fitted in a least square sense (notice 0.5 is not a strong correlation), and the standard deviation equal to 0.26. The strong positive correlation between the inter-event time and the magnitude of the preceding mainshock suggests that the time-predictable model is applicable in the considered region. The value of logT* is calculated using the equation $\log T^* = \log T - 0.01\ M_{min} + 0.05 \log m_0 - 0.98$ corresponding to each M_p and a database is generated. The relation between logT* and M_p is illustrated in Fig. 2 a; where T, M_{min}, log m_o, and M_p are observed values which have their usual meaning.

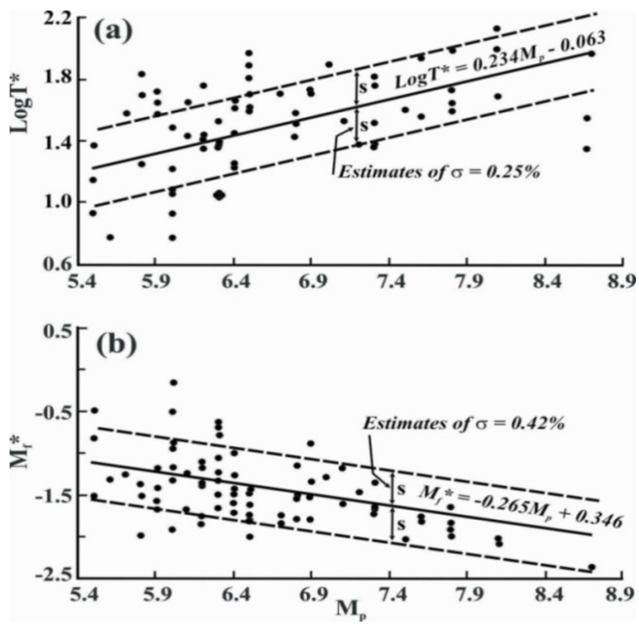

Figure 2. (a) Dependence of the repeat time (T*) on the magnitude of the preceding mainshocks (M_p); and (b) dependence of the magnitude of the following mainshock ($\mathbf{M_f^*}$) on the magnitude of the preceding mainshock (M_p)

Similarly, the values of the magnitude of the successive mainshocks (M_f) were calculated by using same data set (Table 2), and the following empirical relationship is established:

$$M_f = 0.89\ M_{min} - 0.26\ M_p + 0.29 \log m_0 - 5.5 \quad (5)$$

The Equation (5) has correlation coefficient equal to 0.75 and the standard deviation equal to 0.41. The value of M_f^* is computed using the equation $M_f^* = M_f - 0.89\ M_{min} - 0.29 \log m_0 + 5.5$ corresponding to each M_p and a database is generated.

The relation between M_f^* and M_p is illustrated in Fig. 2b; where T, M_{min}, $\log m_o$, and M_p are observed values. The observed negative dependence of the magnitude of the following mainshock on the magnitude of the preceding mainshock indicates that a large mainshock is followed by a small one and vice-versa.

The frequency distribution of log (T/T_t), which is fitted by a normal distribution with mean, $\mu = 0$ and standard deviation, $\sigma = 0.26$ is shown in Figure 3 shows the validity of the model. The frequency distribution of the difference between the observed magnitude (M_F) of the following mainshock and the calculated magnitude (M_f) of the following mainshock, $M_F - M_f$, using the Equation (5) is shown in Fig. 4. This is fitted by a normal distribution curve with $\mu = 0$ and a standard deviation (σ) equal to 0.41.

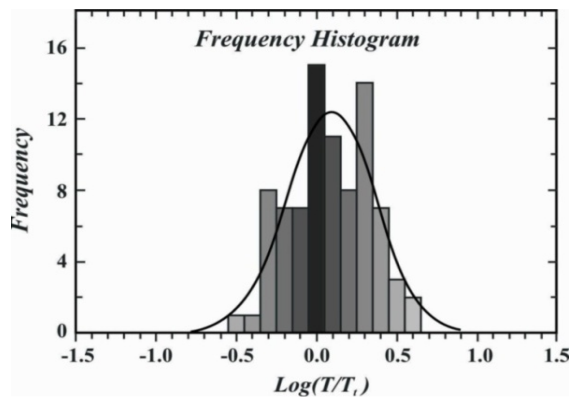

Figure 3. The frequency distribution of the observed repeat times (T) in relation to theoretically estimated repeat times (T_t)

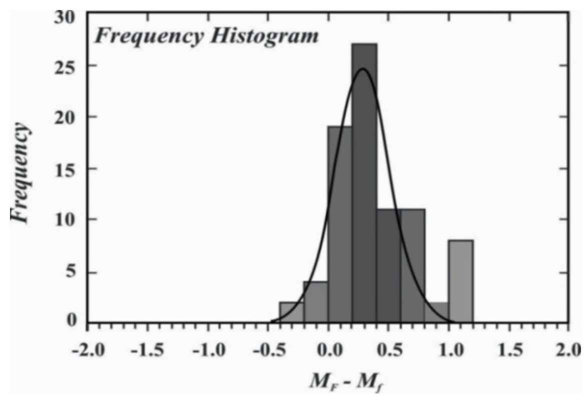

Figure 4. The frequency distribution of difference in observed and calculated magnitudes (M_F. M_f) of the following mainshocks

5. Long-Term Seismic Hazards Prediction

Generally repeat times of large earthquakes in seismogemic sources or fault is considered for long- term earthquake prediction. The earthquake prediction is important for the estimation of seismic hazards in the earthquake prone regions. Since the Time- and Magnitude- Predictable Model is valid for northeast India region, it is possible to evaluate long- term seismic hazards using data from nineteen delineated seismogenic sources.

The developed prediction equation for the considered region as above relation (4) can be used for long- term earthquake prediction. Fig. 2a indicates that there is a significant fluctuation in the observed repeat time, T, and corresponding inter- event time T_t. Owing to this, it is preferred to calculate the conditional probability of next mainshock greater than certain magnitude (e.g. $M_{min} \geq 5.5$ for the considered region) and for given time interval. It is found that the ratio T/T_t follows the lognormal distribution rather than Gaussian or Weibull distributions (Papazachos, 1988; Papazachos and Papaioannou, 1993). Suppose that this distribution holds true for each seismogenic sources of the region, then the conditional probability, P, can be calculated for the occurrence of mainshocks with $M \geq M_{min}$ during the next Δt years from now (i.e. 2010) when the previous such earthquake with magnitude M_p occurred t years ago from present time (2010), by using the following relation (Papazachos and Papaioannou, 1993):

$$P(\Delta t) = \frac{F\left(\frac{X_2}{\sigma}\right) - F\left(\frac{X_1}{\sigma}\right)}{1 - F\left(\frac{X_1}{\sigma}\right)} \quad (6)$$

where $X_2 = log\left(\frac{t+\Delta t}{T_t}\right), and\ X_1 = log\left(\frac{t}{T_t}\right)$

F is the complementary cumulative value of the normal distribution with the mean equal to zero and σ is the standard deviation of the above equation. Given the date and the magnitude of the last event in a seismogenic source along with the uncertainty of the model expressed by its standard deviation $\sigma = 0.26$, the probabilities of the occurrence of the next shallow main shocks with $M_s \geq 5.5$ during the next 10, 20 and 30 years were computed and furnished in Table 3 along with the magnitude of the expected large shallow earthquakes based on the model defined in Equations (4) and (5). In Table 3, the second column gives the name of the seismogenic source and the third column the magnitude of the expected main shock, M_f, as used in Equation (5). The next three columns provide the corresponding probabilities of occurrences which were calculated for the magnitudes of large mainshocks in the next three decadal periods: 2010-2019, 2010–2029 and 2010-2039. The results show significantly high probabilities of earthquake occurrences in these seismogenic sources. It is evident that the absolute values of the probabilities change from source to source signifying different characteristics of an individual seismogenic source. The values thus found are of relative importance and may be refined if more sample data are used in the computation.

6. Discussion

Understanding earthquake generation processes in a region is the key to evaluate future seismic hazards in space and time domains. Presently, the major tools for such evaluation are the systematic analysis of the observed phenomena before and after the earthquakes and use of statistical tools for analysis of seismicity data considering different models with probabilistic approach. Presently, major requirements of the society is the prediction of earthquake related hazards with reasonably high degree of probability which eventually help mitigating expected hazards that would save loss of lives and property. Nonetheless, it is not an easy task to predict precisely the time, magnitude and location associated with future earthquakes with any accuracy, despite many efforts being made worldwide by scientific community. Because of the lack of required density of seismological stations/ instrumentations and technologies, it would be almost impossible to unravel the tectonic processes occurring inside the Earth that eventually trigger the earthquakes. Any wrong prediction of earthquake may pass the wrong message to the public and hence it would be even more hazardous than predicting the seismic hazards. Nevertheless, several researchers are attempting to find suitable earthquake generation models and searching various earthquake precursors for reliable prediction of future seismic hazards in a region.

The study of long-term characteristics of the earthquake generation processes in different seismogenic sources is of fundamental importance for the seismic hazard evaluation. The probabilistic analysis for the occurrence of large earthquakes has not yet been attempted so far in the considered region. The present study discusses the application of the time- and magnitude predictable model and estimation of conditional probability for the occurrence of medium to large size next earthquake and associated magnitude in the next three decades in the region; and to appraise the probabilities of occurrence time and the magnitudes of future earthquake ($M_s \geq 5.5$) in the 19 delineated seismogenic sources of northeast India Himalaya and its adjoining regions (Table 4). A positive slope between the inter-event time and the magnitude of the preceding earthquake indicates that the larger the magnitude of the earthquakes requires a longer return period and vice-versa. This is because the large earthquake releases the accumulated stress to a minimum level; however, the tectonic loading may remain the same. Contrary to this, a weak and negative dependence of the magnitude of the following mainshocks on the repeat times is observed. With this information, The estimated probabilities for the occurrence of medium to large size earthquakes (Ms 5.3-7.1) during the next three decades (2010-2039) indicates that there are very good likelihood for occurring such mainshocks in each of the delineated sources. The probabilities 0.81, 0.91 and 0.96 is observed for the occurrence of large size earthquakes (M 7.1) in Arakan-yoma region (eastern side close to the Sagaing fault) during the next 10, 20 and 30 years respectively. The conditional probabilities P_{10} estimated for different sources during the next decade (2010-2019) shows the highest value 1.0 (P_{10}=1.00) in Eastern Syntaxis (source 7) and in Shillong plateau (source 8) whereas it is slightly lower in other regions ($0.95 \leq P_{10} \leq 0.99$).

Using the estimated value of conditional probability and the maximum magnitude of the expected earthquake during the period 2010-2019, we observed that there are very high probabilities for the occurrence of moderate to large earthquakes (M 6 -7.1) in Eastern Syntaxis (source No. 07), Himalayan Frontal Arc (Source No. 06) and Arakan-yoma regions (source Nos. 10, 11, 13,14, 16 and 18) as given in Table 4. We have also correlated the focal depths of the events occurred in each of these sources during the considered period and observed that the foci of the expected mainshocks, if they occur within the stipulated period, would lie at shallow depths (up to 60 km) in sources 6, 7, 13, 14 and 16 and at intermediate depths (up to 140 km) in sources 10, 11 and 18. All the intermediate expected mainshocks would be located in the middle portion of the delineated intermediate active zones of Arakan-yoma region. The largest expected mainshock (M 7.1) would be shallow focus and would occur in association with the source 16 located to the eastern side close to the Sagaing fault. In view of the above discussion, we expect eight mainshocks ranging in magnitude M 6 to 7.1 to occur during the period 2010-2019. Occurrence of Sikkim earthquake of September 18, 2011 (predicted magnitude 5.8/occurred 6.8; proximity to source no 4 (27.730N, 88.082E)) and Myanmar-India border earthquake of 4th February, 2011 (predicted magnitude 6.2/occurred 6.4; in source No 10 (24.616°N, 94.740°E)), signify the validity of the model and forecasts. This result enables a tentative seismic hazard assessment in areas where no zonation has ever been attempted. More accurate seismic hazard studies require a detailed zonation based on as much data as possible.

Appendix-1

Table 1. Characteristic parameters of each of the seismogenic sources used for estimating probabilities for future seismic hazards (b- seismicity (b- value); a- seismic characteristics of the source; M_{max}- maximum magnitude of earthquake occurred in each seismogenic source, m_o- Seismic moment released annually in each source)

Delineated Regions	Seismogeneic Sources	b	a	M_{max}	Log m_o
Southeastern Tibet	1	0.44	3.14	7.1	26.91679
	2	0.52	4.17	8	28.29487
Eastern Syntaxis	3	0.58	3.98	6	25.81231
Himalayan Frontal Arc	4	0.32	2.24	7.1	26.82221
	5	0.8	5.38	6.7	26.50099
	6	0.76	5.8	7.8	27.97886
Eastern Syntaxis	7	0.43	3.57	8.7	29.12571
Shillong Plateau	8	0.32	2.61	7.1	27.19221
	9	0.98	6.37	6.4	26.25809
Arakan-yoma	10	0.53	4.26	7.8	28.11532
	11	0.36	2.74	7.4	27.39519
	12	0.55	4.16	7.5	27.57337
	13	0.66	4.88	7.6	27.61581
	14	0.39	2.88	7.3	27.21377
	15	0.73	5.3	7.2	27.2236
	16	0.26	2.1	7.8	27.95467
	17	0.78	5.02	6.5	26.11876
	18	0.25	1.95	7.4	27.36918
	19	1.18	7.19	6.1	25.91294

Table 2. Earthquake data used for the parameters determination of empirical relations (M_{min} -magnitude of the smallest mainshock considered; M_p-magnitude of the preceding mainshock; M_f-magnitude of the following mainshock; T_t - repeat time in years; t_p- date of preceding mainshock occurred; t_f – date of occurrence of following mainshock)

Seismogenic sources	M_{min}	M_p	M_f	T_t	t_p	t_f
1	5.7	6.3	5.7	16.36	1980	1996
2	5.8	8.1	5.8	20.68	1951	1972
	5.8	5.8	5.9	20.49	1972	1993
	5.8	5.9	6.3	15.72	1993	2008
	5.9	8.1	5.9	41.17	1951	1993
	5.9	5.9	6.3	15.72	1993	2008
	6.3	8.1	6.3	56.88	1951	2008
3	5.6	6.2	5.8	15.31	1950	1965
	5.6	5.8	5.6	38.18	1965	2003
	5.8	6.2	5.8	15.31	1950	1965
4	5.6	7.1	6.1	16.64	1964	1980
	5.6	6.1	5.6	22.35	1980	2003
	6.1	7.1	6.1	16.64	1964	1980
5	6.0	6.8	6.0	14.04	1950	1964
	6.0	6.0	6.2	3.04	1964	1967

Seismogenic sources	M_{min}	M_p	M_f	T_t	t_p	t_f
	6.2	6.8	6.2	17.08	1950	1967
6	5.7	6.5	5.7	40.61	1964	2005
	6.5	7.8	6.5	17.23	1947	1964
7	5.5	8.7	5.5	34.52	1950	1985
8	5.5	6.8	5.5	9.31	1951	1960
	6.8	7.3	6.8	27.58	1924	1951
9	5.6	6.3	6.4	12.47	1950	1963
	5.6	6.4	5.6	21.53	1963	1984
	5.6	5.6	5.8	3.1	1984	1988
	5.6	5.8	5.6	9.25	1988	1997
	5.8	6.3	6.4	12.47	1950	1963
	5.8	6.4	5.8	24.63	1963	1988
	6.3	6.3	6.4	12.47	1950	1963
10	5.6	7.3	7.8	10.31	1954	1964
	5.6	7.8	6.0	19.13	1964	1983
	5.6	6.0	7.5	4.93	1983	1988
	5.6	7.5	5.6	17.12	1988	2005
	6.0	7.3	7.8	10.31	1954	1964
	6.0	7.8	6.0	19.13	1964	1983
	6.0	6.0	7.5	4.93	1983	1988
	7.3	7.3	7.8	10.31	1954	1964
	7.3	7.8	7.5	24.06	1964	1988
	7.5	7.8	7.5	24.06	1964	1988
11	6.3	6.3	7.4	5.16	1965	1970
	7.0	7.0	7.4	37.96	1932	1970
12	5.5	6.2	6.0	12.08	1950	1962
	5.5	6.0	5.5	7.47	1962	1970
	5.5	5.5	6.9	6.42	1970	1976
	5.5	6.9	6.5	23.82	1976	2000
	6.0	6.2	6.0	12.08	1950	1962
	6.0	6.0	6.9	13.89	1962	1976
	6.0	6.9	6.5	23.82	1976	2000
	6.2	6.2	6.9	25.98	1950	1976
	6.2	6.9	6.5	23.82	1976	2000
	6.5	6.9	6.5	23.82	1976	2000
13	6.1	6.1	6.7	12.59	1958	1971
	6.1	6.7	6.2	23.47	1971	1994
	6.2	6.7	6.2	23.47	1971	1994
	6.5	7.6	6.5	16.62	1932	1948
	6.5	6.5	6.7	23.72	1948	1971
	6.7	7.6	6.7	40.34	1931	1971
14	5.8	7.3	6.2	15.92	1957	1973
	5.8	6.2	5.8	10.93	1973	1984
	6.2	7.3	6.2	15.92	1957	1973
	6.8	6.8	7.3	18.1	1939	1957
15	5.5	6.0	6.4	4.02	1952	1956
	5.5	6.4	6.3	8.39	1956	1964
	5.5	6.3	6.5	5.34	1964	1969
	5.5	6.5	5.5	19.74	1969	1989
	5.5	5.5	5.8	11.24	1989	2000
	5.8	6.0	6.4	4.02	1952	1956
	5.8	6.4	6.3	8.39	1956	1964
	5.8	6.3	6.5	5.34	1964	1969
	5.8	6.5	5.8	30.98	1969	2000
	6.0	6.0	6.4	4.02	1952	1956
	6.0	6.4	6.3	8.39	1956	1964
	6.0	6.3	6.5	5.34	1964	1969
	6.3	6.4	6.3	8.39	1956	1964
	6.3	6.3	6.5	5.34	1964	1969
	6.4	6.4	6.5	13.74	1956	1969
	6.5	7.3	6.5	31.17	1938	1969
16	7.2	7.8	7.2	44.31	1946	1991
17	5.7	6.5	5.7	21.41	1955	1977

Seismogenic sources	M_{min}	M_p	M_f	T_t	t_p	t_f
	5.7	5.7	5.9	20.52	1977	1997
	5.9	6.5	5.9	41.94	1955	1997
18	7.2	7.2	7.4	11.36	1964	1975
19	5.5	5.9	5.5	24.67	1965	1989
	5.5	5.5	6.1	4.68	1989	1994
	5.9	5.9	6.1	29.35	1965	1994

Table 3. The expected magnitude of the following earthquake (M_f) and the corresponding conditional probabilities P_{10}, P_{20} and P_{30} for the occurrence of mainshocks with $M_{min} \geq 5.5$ in northeast India Himalaya and its adjoining regions during the period 2010 to 2039 (M_{min} – magnitude of the smallest mainshock considered; M_p – magnitude of the preceding mainshock; t_p – date of preceding mainshock occurred; m_o – moment rate per year)

Delineated Regions	Seismo-genic sources	M_f	Probability (log normal)			M_{min}	M_p	t_p	Log m_o (dyne-cm/year)
			P10	P20	P30				
Southeastern Tibet	1	5.7	0.95	0.99	1.00	5.5	5.7	1996	26.91679
	2	6.2	0.61	0.90	0.97	5.8	6.3	2008	28.29487
Eastern Syntaxis	3	5.5	0.83	0.96	0.99	5.6	5.6	2003	25.81231
	7	6.4	1.00	1.00	1.00	5.5	5.5	1985	29.12571
Himalayan Frontal Arc	4	5.8	0.88	0.97	0.99	5.6	5.6	2003	26.82221
	5	5.9	0.99	1.00	1.00	6.0	6.2	1967	26.50099
	6	6.2	0.86	0.97	0.99	5.7	5.7	2005	27.97886
Shillong Plateau	8	5.9	1.00	1.00	1.00	5.5	5.5	1960	27.19221
	9	5.6	0.94	0.98	1.00	5.6	5.6	1997	26.25809
Arakan-yoma	10	6.2	0.89	0.98	1.00	5.6	5.6	2005	28.11532
	11	6.1	0.94	0.97	0.98	6.3	7.4	1970	27.39519
	12	5.7	0.80	0.93	0.98	5.5	6.5	2000	27.57337
	13	6.3	0.93	0.98	0.99	6.1	6.2	1994	27.61581
	14	6.0	0.99	1.00	1.00	5.8	5.8	1984	27.21377
	15	5.8	0.91	0.98	0.99	5.5	5.8	2000	27.2236
	16	7.1	0.81	0.91	0.96	7.2	7.2	1991	27.95467
	17	5.6	0.85	0.96	0.99	5.7	5.9	1997	26.11876
	18	6.9	0.91	0.95	0.97	7.2	7.4	1975	27.36918
	19	5.3	0.90	0.97	0.99	5.5	5.5	1989	25.91294

Table 4. Estimated data of time of occurrence and magnitude of future mainshocks predicted during the next 10 years period (2010-2019) in different delineated seismogenic sources in northeast India Himalaya and its adjoining regions using the calculated Conditional Probabilities obtained through the Time- and Magnitude-Predictable model.

Regions	Range of magnitude of the expected mainshock	Conditional probability (P10) for the period 2010-2019	Source zones for the location of predicted earthquakes			Predicted duration
			Sources	Area (x $10^3 km^2$)	Focal depth	
Southeastern Tibet	5.7	0.95	01	18.181	Shallow	2010-2019
Eastern Syntaxis	6.4	1.00	07	09.068	Shallow	2010-2019
Himalayan Frontal Arc	5.8	0.88	04	03.199	Shallow	2010-2019
	5.9	0.99	05	16.290	Shallow	2010-2019
	6.2	0.86	06	25.308	Shallow	2010-2019
Shillong Plateau	5.9	1.00	08	28.107	Shallow	2010-2019
Arakan-yoma fold belt	6.0	0.99	14	04.266	Shallow	2010-2019
	6.1	0.95	11	07.999	Intermediate	2010-2019
	6.2	0.89	10	18.908	Intermediate	2010-2019
	6.3	0.93	13	09.212	Shallow	2010-2019
	6.9	0.91	18	04.376	Intermediate	2010-2019
	7.1	0.81	16	06.981	Shallow	2010-2019

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