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: 

\[ \log T_t = 0.01 M_{\text{min}} + 0.22 M_p - 0.05 \log m_0 + 0.98 \] 

and 

\[ M_f = 0.89 M_{\text{min}} - 0.26 M_p + 0.29 \log m_0 - 5. \]

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 mainshocks 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 (Papazchos and Papaioannou, 1993); New Guinea–Bismark sea region (Karakaisis, 1993); the Western coast of the South and the Central America (Papadimitriou, 1993); Greece (Papazchos, 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.

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, Mmax and log m0 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 Mmax 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, Mp, is represented in the form of

\[ \log T = c M_p + a \]

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 coseismic 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 Papazchos (1992) and its modified form by Papazchos and Papaioannou (1993) is represented by the following two relations:

\[ \log T_i = b M_{min} + c M_p + d \log m_0 + q \]  
\[ M_f = B M_{min} + C M_p + D \log m_0 + m \]

where Ti is the inter-event time measured in years, Mmin is the surface-wave magnitude of the smallest main shock considered, Mf is the magnitude of the following main shock, M0 is the magnitude of the following main shock, m0 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 com-
puter 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:

\[
\log T^* = 0.01 M_{\text{min}} + 0.22 M_p - 0.05 \log m_0 + 0.98
\]  

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 \(\log T^*\) is calculated using the equation \(\log T^* = \log T - 0.01 M_{\text{min}} + 0.05 \log m_0 - 0.98\) corresponding to each \(M_p\) and a database is generated. The relation between \(\log T^*\) and \(M_p\) is illustrated in Fig. 2a; where \(T, M_{\text{min}}, \log m_0,\) and \(M_p\) are observed values which have their usual meaning.

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:

\[
M_f = 0.89 M_{\text{min}} - 0.26 M_p + 0.29 \log m_0 - 5.5
\]  
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 \(M_f^* = M_f - 0.89 M_{\text{min}} - 0.29 \log m_0 + 5.5\) corresponding to each \(M_p\) and a database is generated.

The relation between \(M_f^*\) and \(M_p\) is illustrated in Fig. 2b; where \(T, M_{\text{min}}, \log m_0,\) 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 (\(\sigma\)) equal to 0.41.

5. Long-Term Seismic Hazards Prediction

Generally repeat times of large earthquakes in seismogenic 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, Tt, and corresponding inter-event time Tc. Owing to this, it is preferred to calculate the conditional probability of next mainshock greater than certain magnitude (e.g. Mmin ≥ 5.5 for the considered region) and for given time interval. It is found that the ratio T/Tc 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 ≥ Mmin during the next Δt years from now (i.e. 2010) when the previous such earthquake with magnitude M0 occurred t years ago from present time (2010), by using the following relation (Papazachos and Papaioannou, 1993):

\[
P(\Delta t) = \frac{f(X_2) - f(X_1)}{1 - f(X_2)}
\]

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

F is the complementary cumulative value of the normal distribution with the mean equal to zero and \(\sigma\) 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 \(M_t \geq M_{min}\) 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, \(M_t\) as used in Equation (5). The next three columns provide the corresponding probabilities of occurrences which were calculated for the magnitudes of large main shocks 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/ instrumentation 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 (\(M_t \geq 5.5\)) 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 (Ms 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 ≤ \(P_{10}\) ≤ 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; Mmax- maximum magnitude of earthquake occurred in each seismogenic source, mol Seismic moment released annually in each source)

| Delineated Regions | Seismogenic Sources | b  | a  | Mmax | Log mol |
|-------------------|---------------------|----|----|------|---------|
| 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 | 27.53737 |
|                   | 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 (Mmin -magnitude of the smallest mainshock considered; Mf -magnitude of the preceding mainshock, Ml -magnitude of the following mainshock; Tt - repeat time in years; tp- date of preceding mainshock occurred; tf – date of occurrence of following mainshock)

| Seismogenic sources | Mmin | Mf  | Ml  | Tt   | tp   | tf   |
|---------------------|------|-----|-----|------|------|------|
| 1                   | 5.7  | 6.3 | 5.7 | 16.36| 1980 | 1996 |
| 2                   | 5.8  | 8.1 | 5.8 | 20.68| 1951 | 1972 |
| 3                   | 5.8  | 5.8 | 5.9 | 20.49| 1972 | 1993 |
| 4                   | 5.9  | 8.1 | 6.3 | 15.72| 1993 | 2008 |
| 5                   | 6.3  | 8.1 | 6.3 | 56.88| 1951 | 2008 |
| 6                   | 5.6  | 6.2 | 5.8 | 15.31| 1950 | 1965 |
| 7                   | 5.6  | 5.8 | 5.6 | 38.18| 1965 | 2003 |
| 8                   | 5.8  | 6.2 | 5.8 | 15.31| 1950 | 1965 |
| 9                   | 5.6  | 7.1 | 6.1 | 16.64| 1964 | 1980 |
| 10                  | 5.6  | 6.1 | 5.6 | 22.35| 1980 | 2003 |
| 11                  | 6.1  | 7.1 | 6.1 | 16.64| 1964 | 1980 |
| 12                  | 6.0  | 6.8 | 6.0 | 14.04| 1950 | 1964 |
| 13                  | 6.0  | 6.0 | 6.2 | 3.04 | 1964 | 1967 |
| Seismogenic sources | $M_{\text{rms}}$ | $M_p$ | $M_l$ | $T_1$ | $t_p$ | $t_l$ |
|-------------------|----------------|-------|-------|-------|-------|-------|
| 6                 | 6.2            | 6.8   | 6.2   | 17.08 | 1950  | 1967  |
| 7                 | 5.7            | 6.5   | 5.7   | 40.61 | 1964  | 2005  |
| 8                 | 6.5            | 7.8   | 6.5   | 17.23 | 1947  | 1964  |
| 9                 | 5.5            | 8.7   | 5.5   | 34.52 | 1950  | 1985  |
| 10                | 5.5            | 6.8   | 5.5   | 9.31  | 1951  | 1960  |
| 11                | 6.8            | 7.3   | 6.8   | 27.58 | 1924  | 1951  |
| 12                | 5.6            | 6.3   | 6.4   | 12.47 | 1950  | 1963  |
| 13                | 6.0            | 7.3   | 7.8   | 10.31 | 1954  | 1964  |
| 14                | 6.0            | 7.8   | 6.0   | 19.13 | 1964  | 1983  |
| 15                | 6.0            | 6.0   | 7.5   | 4.93  | 1983  | 1988  |
| 16                | 6.0            | 7.5   | 5.6   | 17.12 | 1988  | 2005  |
| 17                | 6.0            | 7.8   | 6.0   | 10.13 | 1954  | 1966  |
| 18                | 6.0            | 6.0   | 7.5   | 4.93  | 1983  | 1988  |
| 19                | 7.3            | 7.3   | 7.8   | 10.31 | 1954  | 1964  |
| 20                | 6.3            | 7.8   | 7.5   | 24.06 | 1964  | 1988  |
| 21                | 7.5            | 7.8   | 7.5   | 24.06 | 1964  | 1988  |
| 22                | 6.3            | 7.3   | 7.4   | 5.21  | 1965  | 1970  |
| 23                | 7.0            | 7.0   | 7.4   | 37.96 | 1932  | 1970  |
| 24                | 6.5            | 6.2   | 6.0   | 12.08 | 1950  | 1962  |
| 25                | 5.5            | 6.0   | 5.5   | 7.47  | 1962  | 1970  |
| 26                | 5.5            | 5.5   | 6.9   | 6.42  | 1970  | 1976  |
| 27                | 5.5            | 6.9   | 6.5   | 23.82 | 1976  | 2000  |
| 28                | 6.0            | 6.2   | 6.0   | 23.38 | 1976  | 2000  |
| 29                | 6.0            | 6.0   | 6.9   | 13.89 | 1962  | 1976  |
| 30                | 6.0            | 6.9   | 6.5   | 23.82 | 1976  | 2000  |
| 31                | 6.2            | 6.2   | 6.9   | 25.98 | 1950  | 1976  |
| 32                | 6.2            | 6.9   | 6.5   | 23.82 | 1976  | 2000  |
| 33                | 6.5            | 6.9   | 6.5   | 23.82 | 1976  | 2000  |
| 34                | 6.1            | 6.1   | 6.7   | 12.59 | 1958  | 1971  |
| 35                | 6.1            | 6.7   | 6.2   | 23.47 | 1971  | 1994  |
| 36                | 6.2            | 6.7   | 6.2   | 23.47 | 1971  | 1994  |
| 37                | 6.5            | 7.6   | 6.5   | 16.62 | 1932  | 1948  |
| 38                | 6.5            | 6.5   | 6.7   | 23.72 | 1948  | 1971  |
| 39                | 6.7            | 7.6   | 6.7   | 40.34 | 1931  | 1971  |
| 40                | 5.8            | 7.3   | 6.2   | 15.92 | 1957  | 1973  |
| 41                | 5.8            | 6.2   | 5.8   | 10.93 | 1973  | 1984  |
| 42                | 6.2            | 7.3   | 6.2   | 15.92 | 1957  | 1973  |
| 43                | 6.8            | 6.8   | 7.3   | 18.1  | 1939  | 1957  |
| 44                | 5.5            | 6.0   | 6.4   | 4.02  | 1952  | 1956  |
| 45                | 5.5            | 6.4   | 6.3   | 8.39  | 1956  | 1964  |
| 46                | 5.5            | 6.3   | 6.5   | 5.34  | 1964  | 1969  |
| 47                | 5.5            | 6.5   | 5.5   | 19.74 | 1969  | 1989  |
| 48                | 5.5            | 5.5   | 5.8   | 11.24 | 1989  | 2000  |
| 49                | 5.8            | 6.0   | 6.4   | 4.02  | 1952  | 1956  |
| 50                | 5.8            | 6.4   | 6.3   | 8.39  | 1956  | 1964  |
| 51                | 5.8            | 6.3   | 6.5   | 5.34  | 1964  | 1969  |
| 52                | 5.8            | 6.5   | 5.8   | 30.98 | 1969  | 2000  |
| 53                | 6.0            | 6.0   | 6.4   | 4.02  | 1952  | 1956  |
| 54                | 6.0            | 6.4   | 6.3   | 8.39  | 1956  | 1964  |
| 55                | 6.0            | 6.3   | 6.5   | 5.34  | 1964  | 1969  |
| 56                | 6.3            | 6.4   | 6.3   | 8.39  | 1956  | 1964  |
| 57                | 6.3            | 6.3   | 6.5   | 5.34  | 1964  | 1969  |
| 58                | 6.4            | 6.4   | 6.5   | 13.74 | 1956  | 1969  |
| 59                | 6.5            | 7.3   | 6.5   | 31.17 | 1938  | 1969  |
| 60                | 7.2            | 8.7   | 6.2   | 44.31 | 1946  | 1991  |
| 61                | 5.7            | 6.5   | 5.7   | 21.41 | 1951  | 1977  |
| Seismogenic sources | $M_{min}$ | $M_p$ | $M_t$ | $T_t$ | $t_p$ | $t_f$ |
|---------------------|----------|-------|-------|-------|-------|-------|
| 5.7                 | 5.7      | 5.9   | 20.52 | 1977  | 1997  |
| 5.9                 | 6.5      | 5.9   | 41.94 | 1955  | 1997  |
| 7.2                 | 7.2      | 7.4   | 11.36 | 1964  | 1975  |
| 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) | $M_{min}$ | $M_p$ | $t_p$ | $t_f$ | Log $m_o$ (dyne-cm/year) |
|--------------------|----------------------|-------|--------------------------|-----------|-------|-------|-------|--------------------------|
| 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                |
|                    | 4                    | 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 ($P_{10}$) for the period 2010-2019 | Source zones for the location of predicted earthquakes | Predicted duration |
|-----------------------|---------------------------------------------|------------------------------------------------------------|------------------------------------------------------|------------------|
| 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        |
| Shillong Plateau      | 5.9                                         | 0.99                                                       | 05, 16.290, 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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