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Time-predictable model applicability for earthquake occurrence in northeast India and vicinity

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Abstract. Northeast India and its vicinity is one of the seismically most active regions in the world, where a few large and several moderate earthquakes have occurred in the past. In this study the region of northeast India has been considered for an earthquake generation model using earthquake data as reported by earthquake catalogues National Geophysical Data Centre, National Earthquake Information Centre, United States Geological Survey and from book prepared by Gupta et al. (1986) for the period 1906–2008. The events having a surface wave magnitude of $M_s \geq 5.5$ were considered for statistical analysis. In this region, nineteen seismogenic sources were identified by the observation of clustering of earthquakes. It is observed that the time interval between the two consecutive mainshocks depends upon the preceding mainshock magnitude (M_p) and not on the following mainshock (M_f). This result corroborates the validity of time-predictable model in northeast India and its adjoining regions. A linear relation between the logarithm of repeat time (T) of two consecutive events and the magnitude of the preceding mainshock is established in the form $\text{Log}T = cM_p + a$, where "c" is a positive slope of line and "a" is function of minimum magnitude of the earthquake considered. The values of the parameters "c" and "a" are estimated to be 0.21 and 0.35 in northeast India and its adjoining regions. The less value of c than the average implies that the earthquake occurrence in this region is different from those of plate boundaries. The result derived can be used for long term seismic hazard estimation in the delineated seismogenic regions.

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1 Introduction

Reid (1910) has given a theory for the earthquake cycle (periodicity) called elastic rebound theory. According to him, due to continuous loading motions on fractured rock, strain accumulates on either side of it. When strain reaches a critical value (elastic limit) the frictional resistance is overcome by a fault, and then the displacement on two sides of the fault takes place towards a position of minimum strain resulting in the occurrence of an earthquake. Again, the accumulation of strain begins for a future earthquake in the same fault after releasing the stored strained energy during the earthquake. This periodical nature of faults becomes an important factor for the prediction of earthquakes. The time-independent models assume that seismicity does not change with time but only with space. Most of the studies related to seismicity and seismic hazard assessment are based on time-independent models (Papazachos et al., 1994). These models are based on the Poission distribution for time and Gutenberg-Richter formula for magnitude distribution. The researchers worked for and searched for a time-dependent seismicity model to fulfill the limitations and inadequacy of independent models. During the last three decades, several attempts have been made to assess time-dependent seismicity models. This attempt led to the conclusion that repeat times for earthquakes occurring in single fault or plate boundaries support time-predictable models.

Two time-dependent seismicity models have been proposed by Shimazaki and Nakata (1980): the slip-predictable model and the time-predictable model. With these models, the size and time of occurrence of future earthquakes can be predicted. Later on, the time-predictable model was modified (Sykes and Quittmeyer, 1981; Anagnos and Kiremidjian, 1984; Papazachos, 1989, 1992) and the slip-predictable model (Kiremidjian and Anagnos, 1984). Earthquake generation processes in different regions of the world were studied.

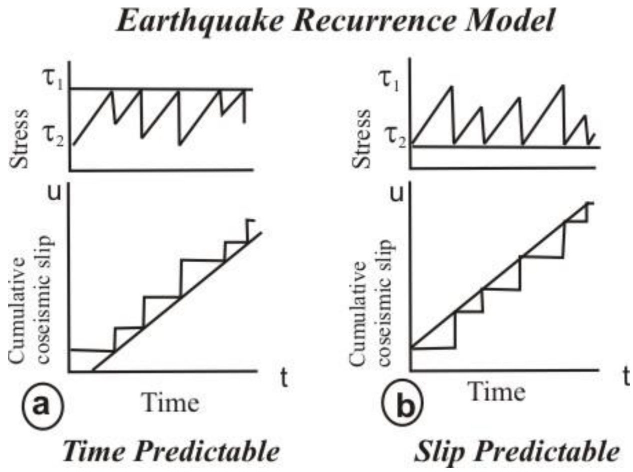

Fig. 1. Earthquake Recurrence Model: **(a)** time-predictable model showing stress buildup to a certain value (τ_1) and non-uniform stress drop; and **(b)** slip predictable-model illustrating non-uniform stress buildup and stress drop to a certain minimum value (τ_2) (after Shimazaki and Nakata, 1980).

These models are used by several researchers for earthquake prediction at different seismogenic regions of the world. Yet, several studies have shown that the time-predictable model was found far better for seismic hazard estimation and earthquake prediction compared to the slip-predictable model (Sykes and Quittmeyer, 1981).

After lengthy work in the field of earthquake recurrence models, the researchers have developed another model called the magnitude-predictable model. This model gives the relation between the magnitudes of the preceding and the following earthquake and indicates that the larger the magnitude of the preceding mainshock, the smaller the magnitude of the following mainshock (Papazachos, 1992). Soon after this, the time-predictable and magnitude-predictable models were combined to a single one called the regional time- and magnitude-predictable seismicity model, which holds for seismogenic regions (or sources) including the main fault and other smaller faults (Papazachos and Papaioannou, 1993).

The earthquake recurrence models were proposed based on Reid's concept of the elastic rebound theory, i.e. that successive earthquakes occur when stress reaches a critical value in a fault of seismogenic sources. Figure 1 shows the two levels of stresses, τ_1 and τ_2, upper and lower level, respectively. These stresses are responsible for controlling the behavior of a fault in the earthquake generation process. When τ_1 is constant, the model is said to be time predictable (Fig. 1a). In this case, stress drop changes to different shocks. When τ_2 is constant, the model is said to be slip predictable. In this case, earthquakes start at variable states of stress (Fig. 1b).

In the time-predictable model, the time interval between two large earthquakes is proportional to the slip amount of the preceding earthquake and a large earthquake occurs when the stress has reached a fixed, limiting value. Similarly, in the case of the slip-predictable model, the time interval between two, successive, large earthquakes is proportional to the slip amount of the next large earthquake. In general, only the size of a future earthquake can be predicted by the slip-predictable model and only the time of its occurrence can be predicted by the time predictable model. Several scientists have applied this model (Mogi, 1985; Papazachos, 1989; Shanker, 1990; Shanker and Singh, 1996, 2007; Paudyal et al., 2008) at different seismogenic regions of world. In the present paper, we are testing the validity of the time-predictable model for earthquake generation in northeast India and its adjoining regions.

2 Earthquake data and sesimogenic sources

An area bounded by 20°–32° N and 88°–98° E has been considered in this study. The region includes the northeast Indian Himalaya, Bhutan, Bangladesh, Burma and southern Tibet. The region is in the eastern part of the Himalayan belt situated at the boundary of the Eurasian and Indian plates. The region consists of several higher peaks, thrusts, faults and lineaments. The region is seismically active and posseses a complex geological and tectonic setup. Several researchers (Evans, 1964; Desikachar, 1974; Nandy, 2001; Acharyya, 2005, and others) have explained the geology and tectonic environment of the region in their important publications.

The earthquake data are compiled using the earthquake catalogues of the National Geophysical Data Center (NGDC), Colorado, National Earthquake Information Center (NEIC), USGS (United States Geological survey), and ISC (International Seismological Centre). Similarly data are taken from the book Seismicity of Northeast India by Gupta et al. (1986). Earthquake data has been considered for the period 1906–2008 in this study. The magnitudes given in body wave magnitudes (M_b) were converted to surface wave magnitude and events were considered for the surface wave magnitude of $M_s \geq 5.5$. The seismogenic sources of northeast India and its adjoining regions were divided into nineteen zones for events $M_s \geq 5.5$, considering the criteria designed by Papazachos (1989): seismicity status, faulting nature, geological environment and clustering pattern of events (Fig. 2). Most of the sources consist of at least one mainshock with magnitude $M_s \geq 7.1$. The seismogenic sources are separated by shaded elliptical boundaries.

Two sources 1 and 2 have been identified in southern Tibet i.e. to the north of ITS (Indus Sangpo Suture). No major faults/lineaments appeared in these sources. The orientation of these sources are along the NE-SW of major axis of the demarcated elliptical bound. Source 2 is related to a great earthquake of a magnitude of M 8 of 1951. Source 3 situated just south of the eastern part of ITS, consists of events of magnitude below $M_s \leq 6.0$. Sources 4, 5 and 6 are situated just north or at the MCT (Main Central Thrust). The region

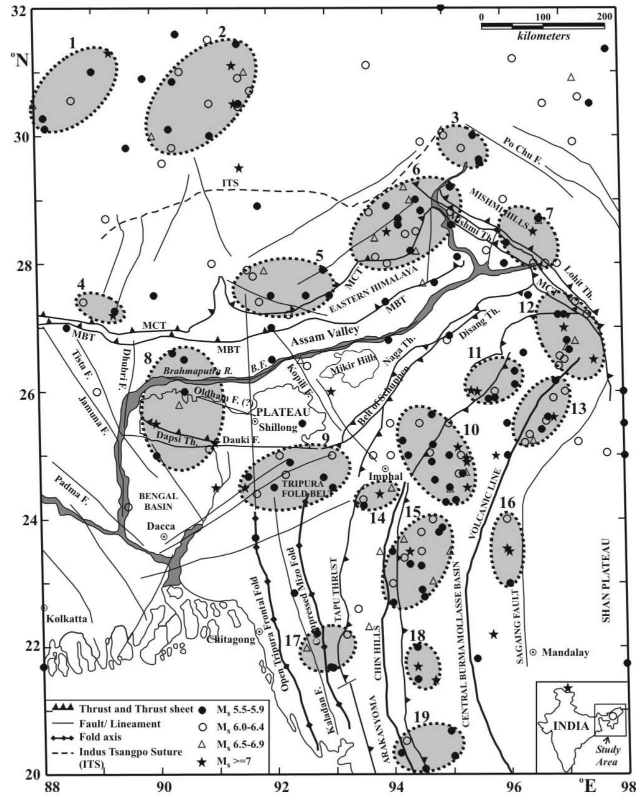

Fig. 2. Earthquake plots with $M_s \geq 5.5$ for the period 1906–2008 in northeast India and its adjoining regions with nineteen seismogenic sources over major tectonic features of the area. The seismogenic sources are separated by shaded elliptical boundaries.

near this thrust is said to be seismically active. Sources 4 and 5 contain fewer earthquakes while source 6 consists of a large number of events with varying magnitudes; these sources are seismically active. Source 7, situated between the Mishmi and Lohit thrusts, is a seat of the great Assam earthquake. It occurred on 15 August 1950 and its magnitude M was 8.7. It caused great destruction throughout Upper Assam, Abor and the Mishmi hills of the state of Arunachal. About 1520 people were killed by this earthquake. The thrusts associated with this region are seismically active. Source 8 lies at the western part of Shillong Plateau, where there are several faults and thrusts, such as the Dauki fault, Dhubri fault, Brahamputra fault and Dapsi thrusts, which are seismically active. In this region, the Dubri earthquake of 1930, having a magnitude of M 7.1, occurred. Source 9, just south of the Shillong Plateau, is seismically active due to the presence of the Sylhet fault with the Tripura folded belt. This source has earthquakes with magnitudes of less than 6.5. This region is the seat of the Cachar earthquake of 1984 with a magnitude of 5.8. Sources 10, 11, 12, 14 and 15, situated in Indo-Burman Ranges, consist of large numbers of earthquakes of varying magnitudes. In this region, seismicity is related to the subduction of the Indian plate underneath the Southeast Asian plate due to the northeastward motion of India (Desikachar, 1974). This region has suffered about 10 large earthquakes ($M \geq 7.0$) during the last 100 years. The Indo-Myanmar Border Earthquake of 1988 with a magnitude of M 7.8, occurred in the source 10. Source 13, situated at volcanic line , has a large number of earthquakes. This region is also seismically active in northeast India. Source 17 is affected by the Tapu thrust. Source 18 lies at the central Burma and source 19 near to Arakan Yoma are also seismically sensitive.

3 Methodology applied and calculation

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

$$\mathrm{Log}T = cM_p + a \quad (1)$$

where the constant c is the gradient of least square line with a positive value and a is a constant function of the magnitude. These constants depend upon the nature of the source. Since the preceding magnitude of M_p is linearly related to the logarithm of the coseismic slip, Eq. (1) indicates that the time between the two successive main shocks in a seismogenic source is linearly related to the coseismic slip of the previous main shock. 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 repeat time, T, shows a variation from one source to another source due to a difference in the value of a. For the validity of the time-predictable model established for a region the value of c, the coefficient of M_p, is always positive (Qin et al., 1999). The worldwide value of this coefficient has been calculated as 0.33 (Papazachos and Papadimitriou, 1997). Similarly the regional value of c for northeast India, Greece, Aegean area, the western coast of South and Central America and for Nepal Himalaya is estimated to be as 0.36, 0.32, 0.35, 0.21 and 0.32, respectively.

The seismic moment, M_o (moment released), for an individual earthquake in the sequence is planned from the surface wave magnitude using the following relationship (Purcaru and Berckhemer, 1978):

$$\mathrm{Log}M_0 = 1.5M_s + 16.1$$

Similarly, the moment magnitude, M_w (cumulative magnitude), for all the considered events in the sequence is derived using the relation given by Hanks and Kanamori (1979):

$$M_w = 2/3\log M_o - 10.7$$

To find the preceding and following mainshocks, M_{min} is considered in each source. Calculated values of M_{min}, M_p, M_f (following mainshock), T (repeat time) are given in Table 1. The following method is used to find the above parameters. The sixth column of Table 1 represents cumulative magnitude. In the calculation, we have considered the

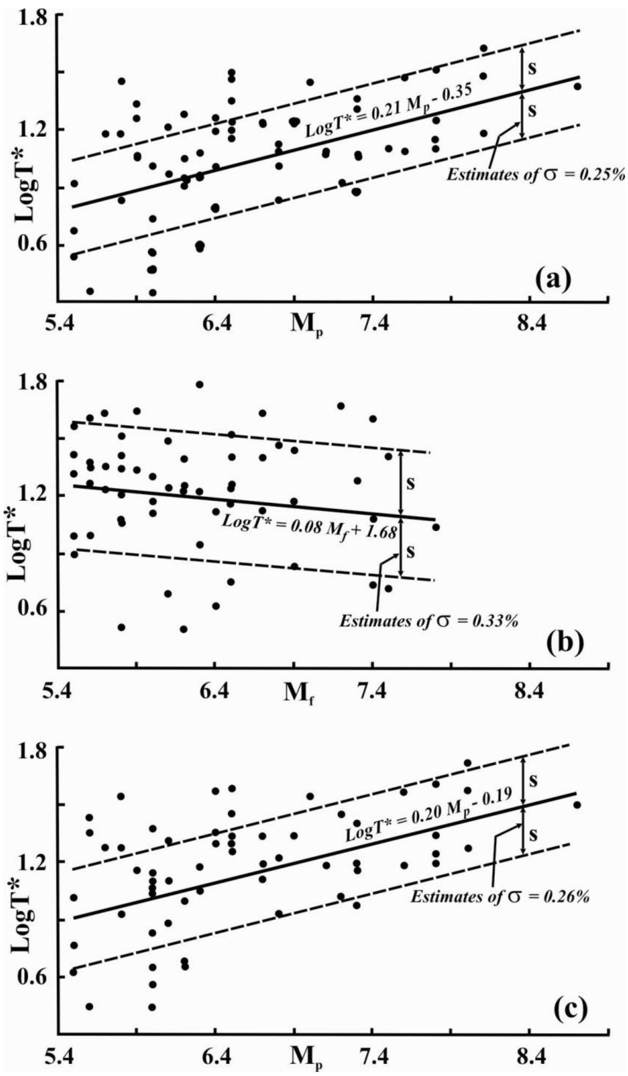

Fig. 3. Plot of T^* (repeat time) against M_p (the preceding mainshock magnitude) and M_f (the following mainshock magnitude) with their estimated regression lines (with residual, s and standard deviation, σ. All earthquakes are considered in panels **(a)** and **(b)**, whereas in panel **(c)**, the associated aftershocks and foreshocks were excluded.

completeness of data as M 7.5 for 1897, M 6.5 for 1930 and M 5.5 for 1950. For source 1, 7.1 (1934), 6.3 (1980) and 5.7 (1996) are cumulative magnitudes. Here for $M_{min} = 5.7$, there are two earthquakes (in 1980 and 1996) and one repeat time with preceding and following mainshocks. So, for this case preceding M_p and following M_f, the magnitudes are 6.3 and 5.7, respectively, with return periods of 16.36 yr (T). In this source we cannot consider the earthquake of a magnitude of 7.1 (1934) for determining M_p and M_f because it occurred before 1950 (due to incompleteness of data). Same procedure was adopted for all the sources to estimate the aforementioned parameters.

The data given Table 1 were used to find the linear relation between $\log T$ and M_p

$$\mathrm{Log}T = cM_p + a \tag{2}$$

The correlation coefficient of the above equation is 0.50. The value of c is affected by both a and M_{min} considered in each case. Therefore, to reduce $\log T$ the value of constant a was calculated by using $c = 0.209$ for all available data of T and M_p from Table 1. Then, the average value $\bar{a}_m$ was calculated for all a. By applying the same method, different values of a_{mn} were calculated corresponding to the different sets of M_{min} and T and average, $\bar{a}_{mn}$, was determined. The difference of $\bar{a}_m - \bar{a}_{mn}$ was added to $\log T$ to obtain

$$\mathrm{Log}T^* = \log T + \bar{a}_m - \bar{a}_{mn} \tag{3}$$

Where T^* gives the average time of the event for all the sesimogenic sources.

Figure 3a shows the plotting of log T^* and M_p with regression line equation

$$\mathrm{Log}T^* = 0.21M_p - 0.35 \tag{4}$$

The correlation coefficient of the equation of the above equation is 0.51. This equation reveals that the average repeat time increases with the increase of value of M_p. This means that the time-preditable model is valid for the region of northeast India.

The linear relation derived between Log$T$ and M_p shows the applicability of the time-predictable model in the considered region. This relation can be used for the estimation of the recurrence period of earthquakes in seismogenic sources in northeast India and its vicinity. Thus, this result becomes helpful for long-term earthquake prediction and time-dependent seismic hazard evaluation in the region. This model would be more fruitful if a sufficient amount of reliable seismicity data were available for the region.

Again, the same database and method was applied to obtain the relation between T^* and the following mainshock magnitude M_f (Fig. 3b). The regression line was obtained as:

$$\mathrm{Log}T^* = -0.08M_f + 1.68 \tag{5}$$

The above equation has a smaller correlation coefficient than 0.15. The negative slope graphically indicates that less time is needed for a large forthcoming earthquake, which is contentious to slip-predictable model. The slip-predictable model is not applicable (valid) to the regions considered.

Another regression line was obtained from the same data set and the procedure excluding foreshocks and aftershocks as (Fig. 3c);

$$\mathrm{Log}T^* = 0.20M_p - 0.19 \tag{6}$$

with the correlation coefficient 0.49. The statistical analyses and interpretation of these equations derived and plotted in

Table 1. Earthquake Data having a magnitude of $M_S \geq 5.5$ used for testing the validity of Time- and Magnitude-Predictable Model; a = aftershocks, f = foreshocks, M = cumulative magnitude.

Seismogenic sources	Date dd.mm.yy	Location Lat. ° N	Long. ° E	M_S	M_w	M_{min}	M_p	M_f	T (years)
NEI-1	15.12.1934	31.3	89.3	7.1	7.1	5.7	6.3	5.7	16.36
	03.01.1935	30.5	88.0	6.5	a				
	22.02.1980	30.6	88.6	6.3	6.3				
	03.07.1996	30.1	88.2	5.5	5.7				
	25.08.1998	30.3	88.2	5.5	a				
NEI-2	17.11.1951	31.0	91.6	6.8	f	5.8	8.1	5.8	20.68
	18.11.1951	30.9	91.5	6.3	a	5.8	5.8	5.9	20.49
	18.11.1951	31.1	91.4	8.0	8.1	5.8	5.9	6.3	15.72
	18.11.1951	30.5	91.5	6.0	a	5.9	8.1	5.9	41.17
	18.11.1951	30.5	91.5	6.0	a	5.9	5.9	6.3	15.72
	26.12.1951	31.0	90.5	6.3	a	6.3	8.1	6.3	56.88
	17.08.1952	30.5	91.5	7.5	a				
	29.12.1955	30.1	90.3	5.8	a				
	10.06.1959	30.0	91.0	5.8	a				
	22.07.1972	31.4	91.5	5.8	5.8				
	18.01.1993	30.8	90.4	5.9	5.9				
	06.10.2008	29.8	90.4	6.3	6.3				
NEI-3	23.02.1950	29.8	95.3	6.0	6.2	5.6	6.2	5.8	15.31
	22.08.1950	30.0	95.5	5.5	a	5.6	5.8	5.6	38.18
	01.09.1950	30.0	95.5	6.0	a	5.8	6.2	5.8	15.31
	15.06.1965	29.6	95.6	5.8	5.8				
	18.08.2003	29.6	95.6	5.6	5.6				
NEI-4	27.03.1964	27.2	89.3	7.1	7.1	5.6	7.1	6.1	16.64
	19.11.1980	27.4	88.8	6.1	6.1	5.6	6.1	5.6	22.35
	25.03.2003	27.3	89.3	5.6	5.6	6.1	7.1	6.1	16.64
NEI-5	16.08.1950	27.9	91.9	6.7	6.8	6.0	6.8	6.0	14.04
	17.08.1950	27.9	91.6	6.0	a	6.0	6.0	6.2	3.04
	23.02.1954	27.8	91.7	6.0	a	6.2	6.8	6.2	17.08
	13.02.1958	27.5	92.0	5.5	a				
	01.09.1964	27.2	92.3	6.0	6.0				
	26.09.1966	27.5	92.6	5.6	f				
	15.09.1967	27.4	91.8	6.2	6.2				
NEI-6	29.07.1947	28.5	94.0	7.8	7.8	5.7	6.5	5.7	40.61
	16.08.1950	29.2	95.1	5.8	a	6.5	7.8	6.5	17.23
	16.08.1950	29.2	95.1	6.0	a				
	16.08.1950	29.2	95.1	5.5	a				
	16.08.1950	29.2	95.1	6.0	a				
	17.08.1950	29.2	95.1	5.8	a				
	17.08.1950	29.2	95.1	6.2	a				
	17.08.1950	29.2	95.1	5.5	a				
	17.08.1950	29.2	95.1	6.0	a				
	18.08.1950	29.2	95.1	6.0	a				
	20.08.1950	29.2	95.1	5.5	a				
	21.08.1950	29.2	95.1	6.1	a				
	22.08.1950	28.7	94.2	5.7	a				
	22.08.1950	29.2	95.1	6.0	a				
	23.08.1950	29.2	95.1	5.8	a				
	25.08.1950	29.2	95.1	6.0	a				
	29.08.1950	29.2	95.1	6.0	a				
	03.09.1950	28.7	94.2	6.0	a				

Table 1. Continued.

Seismogenic sources	Date dd.mm.yy	Location Lat. ° N	Long. ° E	M_s	M_w	M_{min}	M_p	M_f	T (years)
	03.09.1950	29.2	95.1	6.0	a				
	11.09.1950	29.2	95.1	6.0	a				
	13.09.1950	28.7	94.2	6.6	a				
	14.09.1950	29.2	95.1	6.0	a				
	08.10.1950	29.2	95.1	6.4	a				
	03.01.1951	29.0	94.4	6.6	a				
	04.01.1951	28.6	94.2	5.6	a				
	08.02.1951	28.2	94.4	5.8	a				
	21.02.1951	28.9	94.0	5.8	a				
	06.03.1951	28.8	95.1	6.4	a				
	12.03.1951	28.2	94.5	6.5	a				
	14.04.1951	28.4	93.8	6.5	a				
	22.04.1951	29.2	94.3	6.5	a				
	18.10.1951	28.8	93.7	6.0	a				
	26.05.1952	28.5	94.5	6.0	a				
	25.08.1952	28.0	94.0	6.0	a				
	08.10.1963	28.6	95.1	5.5	f				
	21.10.1964	28.1	93.8	6.4	6.5				
	14.03.1967	28.5	94.3	6.2	a				
	01.06.2005	28.8	94.6	5.7	5.7				
NEI-7	15.08.1950	28.5	96.5	8.7	8.7	5.5	8.7	5.5	34.52
	15.08.1950	28.7	96.6	5.5	a				
	15.08.1950	28.7	96.6	6.0	a				
	15.08.1950	28.7	96.6	6.0	a				
	15.08.1950	28.7	96.6	6.0	a				
	15.08.1950	28.7	96.6	6.0	a				
	15.08.1950	28.7	96.6	6.0	a				
	16.08.1950	28.7	96.6	6.6	a				
	16.08.1950	28.7	96.6	6.3	a				
	18.08.1950	28.7	96.6	6.4	a				
	18.08.1950	28.7	96.6	5.8	a				
	18.08.1950	28.7	96.6	6.0	a				
	19.08.1950	28.7	96.6	6.0	a				
	23.08.1950	28.7	96.6	6.0	a				
	24.08.1950	28.0	96.5	6.3	a				
	02.09.1950	28.7	96.6	6.0	a				
	04.09.1950	28.7	96.6	6.0	a				
	03.10.1950	28.0	96.7	6.3	a				
	30.10.1950	28.0	96.9	6.0	a				
	21.07.1951	28.7	96.6	6.0	a				
	21.02.1985	28.3	96.0	5.5	5.5				
NEI-8	02.07.1930	25.5	90.0	7.1	a	5.5	6.8	5.5	9.31
	07.04.1951	25.8	90.4	6.8	6.8	6.8	7.3	6.8	27.58
	29.07.1960	26.5	90.5	5.5	5.5				
NEI-9	29.12.1950	24.4	91.7	6.3	6.3	5.6	6.3	6.4	12.47
	12.12.1957	24.5	93.0	5.5	a	5.6	6.4	5.6	21.53
	19.06.1963	25.0	92.1	6.4	6.4	5.6	5.6	5.8	3.1
	30.12.1984	24.7	92.8	5.6	5.6	5.6	5.8	5.6	9.25
	06.02.1988	24.7	91.6	5.8	5.8	5.8	6.3	6.4	12.47
	08.05.1997	24.9	92.3	5.6	5.6	5.8	6.4	5.8	24.63
						6.3	6.3	6.4	12.47

Table 1. Continued.

Seismogenic sources	Date dd.mm.yy	Location Lat. ° N	Long. ° E	M_s	M_w	M_{min}	M_p	M_f	T (years)
NEI-10	02.06.1934	24.5	95.0	6.5	a	5.6	7.3	7.8	10.31
	30.04.1952	25.5	94.5	6.0	f	5.6	7.8	6.0	19.13
	28.11.1952	25.0	95.2	6.0	f	5.6	6.0	7.5	4.93
	21.03.1954	24.5	95.3	7.3	7.3	5.6	7.5	5.6	17.12
	08.09.1955	25.0	95.0	5.6	a	6.0	7.3	7.8	10.31
	28.05.1957	25.5	95.0	6.0	a	6.0	7.8	6.0	19.13
	26.06.1963	24.3	95.1	5.5	f	6.0	6.0	7.5	4.93
	12.07.1964	24.9	95.3	7.8	7.8	7.3	7.3	7.8	10.31
	18.02.1965	25.0	94.3	5.5	a	7.3	7.8	7.5	24.06
	30.09.1969	25.6	94.7	5.5	a	7.5	7.8	7.5	24.06
	29.12.1971	25.2	94.7	5.8	a				
	30.08.1983	25.0	94.7	6.0	6.0				
	18.05.1987	25.2	94.2	5.9	f				
	06.08.1988	25.1	95.1	7.3	7.5				
	09.01.1990	24.7	95.3	6.7	a				
	23.01.1991	24.7	95.2	5.5	a				
	15.04.1992	24.3	94.9	5.6	a				
	08.08.1994	24.7	95.2	6.4	a				
	06.05.1995	25.0	95.3	7.1	a				
	18.09.2005	24.6	94.7	5.6	5.6				
NEI-11	14.08.1932	26.0	95.5	7.0	7.0	6.3	6.3	7.4	5.16
	27.03.1964	25.9	95.8	5.5	f	7.0	7.0	7.4	37.96
	03.06.1964	25.9	95.7	5.5	f				
	30.05.1965	26.0	95.8	6.2	6.3				
	30.01.1967	26.1	96.1	5.6	a				
	29.08.1969	26.3	96.1	5.5	f				
	29.07.1970	26.0	95.4	7.4	7.4				
NEI-12	12.12.1908	26.5	97.5	7.5	7.5	5.5	6.2	6.0	12.08
	22.08.1950	27.2	97.4	6.0	6.2	5.5	6.0	5.5	7.47
	23.08.1950	27.2	96.9	5.9	a	5.5	5.5	6.9	6.42
	04.05.1955	27.2	97.0	5.8	a	5.5	6.9	6.5	23.82
	22.09.1962	26.5	97.0	6.0	6.0	6.0	6.2	6.0	12.08
	10.03.1970	26.8	97.0	5.5	5.5	6.0	6.0	6.9	13.89
	30.05.1975	26.6	96.9	6.0	f	6.0	6.9	6.5	23.82
	12.08.1976	26.7	97.0	6.9	6.9	6.2	6.2	6.9	25.98
	28.11.1984	26.6	97.1	5.7	a	6.2	6.9	6.5	23.82
	07.06.2000	26.8	97.2	6.5	6.5	6.5	6.9	6.5	23.82
NEI-13	27.01.1931	25.6	96.8	7.6	7.6	6.1	6.1	6.7	12.59
	16.08.1950	25.9	96.8	6.0	a	6.1	6.7	6.2	23.47
	16.08.1950	25.9	96.8	6.0	a	6.2	6.7	6.2	23.47
	16.08.1950	25.9	96.8	6.0	a	6.5	7.6	6.5	16.62
	17.08.1950	25.9	96.8	6.0	a	6.5	6.5	6.7	23.72
	17.08.1950	25.9	96.8	6.0	a	6.7	7.6	6.7	40.34
	06.01.1958	25.6	96.7	5.8	f				
	28.10.1958	25.2	96.3	6.0	6.1				
	30.05.1971	25.3	96.4	6.1	f				
	30.05.1971	25.2	96.4	6.7	6.7				
	06.04.1994	26.2	96.8	5.7	f				
	21.11.1994	25.5	96.7	6.0	6.2				
	30.12.1997	25.4	96.6	5.8	a				

Table 1. Continued.

Seismogenic sources	Date dd.mm.yy	Location Lat. ° N	Long. ° E	M_s	M_w	M_{min}	M_p	M_f	T (years)
NEI-14	27.05.1939	24.5	94.0	6.8	6.8	5.8	7.3	6.2	15.92
	01.07.1957	24.4	93.8	7.3	7.3	5.8	6.2	5.8	10.93
	31.05.1973	24.3	93.5	6.2	6.2	6.2	7.3	6.2	15.92
	06.05.1984	24.2	93.5	5.8	5.8	6.8	6.8	7.3	18.1
NEI-15	14.04.1938	23.5	95.0	6.8	f	5.5	6.0	6.4	4.02
	16.08.1938	23.5	94.3	7.2	7.3	5.5	6.4	6.3	8.39
	11.05.1940	23.7	94.2	6.5	a	5.5	6.3	6.5	5.34
	15.01.1952	23.8	94.5	6.0	6.0	5.5	6.5	5.5	19.74
	21.01.1956	23.0	94.0	6.1	6.4	5.5	5.5	5.8	11.24
	29.02.1956	23.4	94.2	6.0	a	5.8	6.0	6.4	4.02
	19.09.1956	23.5	94.5	6.1	a	5.8	6.4	6.3	8.39
	28.09.1963	22.9	94.5	5.8	f	5.8	6.3	6.5	5.34
	13.06.1964	23.0	94.0	6.2	6.3	5.8	6.5	5.8	30.98
	25.02.1965	23.8	94.8	5.5	a	6.0	6.0	6.4	4.02
	05.12.1965	23.3	94.3	5.5	a	6.0	6.4	6.3	8.39
	17.10.1969	23.1	94.7	6.5	6.5	6.0	6.3	6.5	5.34
	27.07.1973	23.3	94.5	5.5	a	6.3	6.4	6.3	8.39
	15.07.1989	22.8	94.5	5.5	5.5	6.3	6.3	6.5	5.34
	11.10.2000	23.9	94.9	5.8	5.8	6.4	6.4	6.5	13.74
						6.5	7.3	6.5	31.17
NEI-16	12.09.1946	23.5	96.0	7.8	7.8	7.2	7.8	7.2	44.31
	05.01.1991	23.5	96.0	7.2	7.2				
	15.06.1992	24.0	96.0	6.3	a				
NEI-17	14.12.1955	22.0	92.5	6.5	6.5	5.7	6.5	5.7	21.41
	12.05.1977	21.6	92.9	5.7	5.7	5.7	5.7	5.9	20.52
	21.11.1997	22.2	92.7	5.7	5.9	5.9	6.5	5.9	41.94
	13.11.2000	21.6	92.9	5.6	a				
NEI-18	27.02.1964	21.7	94.4	7.2	7.2	7.2	7.2	7.4	11.36
	15.12.1965	22.0	94.4	5.5	a				
	15.12.1966	21.5	94.4	5.8	a				
	08.07.1975	21.5	94.7	7.4	7.4				
NEI-19	22.01.1965	20.1	94.5	5.6	5.9	5.5	5.9	5.5	24.67
	01.06.1965	20.3	95.0	5.6	a	5.5	5.5	6.1	4.68
	15.02.1967	20.3	94.1	5.6	a	5.9	5.9	6.1	29.35
	24.09.1989	20.7	94.9	5.5	5.5				
	29.05.1994	20.5	94.2	6.1	6.1				

Fig. 3 suggest that extreme vales are obtained if and only if the scattered data in a scattergram lie on a perfectly straight line that is, only if LogT^* depending only on the sign of c (slope). In this case the LogT^* and M_p or M_f whatever be the case, are said to be perfectly correlated; for any other than a perfectly linear relationship, the correlation coefficient is less than 1 (in our case). The point estimates of parameters are also indicated in these figures with residual, s and standard deviation σ, connote the correctness of the data.

4 Discussions and conclusions

Probabilistic estimates of earthquake hazard use various models for the temporal distribution of earthquakes, including the "time-predictable" recurrence model formulated by Shimazaki and Nakata (1980) which incorporates the concept of elastic rebound. This model is thought to encompass some of the physics behind the earthquake cycle, in that earthquake probability increases with time. The time-predictable model is therefore often preferred when adequate data are available, and it is incorporated in hazard predictions for many earthquake-prone regions. Several researchers have reported that the time-predictable model for earthquake generation is applicable only in a single fault or simple plate boundaries. However, Papazachos (1989) showed that this model can also be applied in several seismotectonic environments with various fault systems as he did during his study in Greece. Again, the model failed in various regions having a complex tectonic setting such as Parkfield, California (Murray and Segall, 2002). The time-predictable model is applied for earthquake predictions in earthquake-prone areas.

Shanker (1990) and Singh et al. (1992) tested the validity of time-predictable model in northeast India considering four seismogenic sources. In the present study, the identified nineteen seismogenic sources in northeast India and its adjoining regions show diverse seismotectonic environments. The number of fault plane solutions in the seismogenic sources 1 and 2, situated in the Tibetan region, show normal faulting while the other sources 3 to 19 show thrust faulting with a strike slip component (Ni and Barazangi, 1984; Verma and Kumar, 1987; Chen and Molnar, 1990; Mukhopadhyay, 1992; Singh, 2000). For the region considered, the positive correlation between the time interval of the events (repeat time) and the magnitude of the preceding earthquake shows that the model is suitable. But the value of the parameter c is less than the average value of 0.33 that is obtained from the events occurred in the plate boundary in the world (Papazachos and Papadimitriou, 1997). The correlation between the recurrence period of the large earthquakes and the magnitude of the preceding strong events is weaker, implying that earthquake occurrences in the considered regions are different from those in plate boundary. This may be a matter of future debate on the difference between the mechanisms of earthquake occurrence in plate boundary and that ocurring in the continent.

The study of the applicability of the time-predictable model for earthquake occurrence in different regions is significant for long-term earthquake hazard evaluation. It is also helpful in understanding earthquake genesis under different tectonic environments. Such topics should be studied further both in theory and practice. This preliminary work will be applied to develop long-term risk scenarios for the region of northeast India, detailed research in this area has been started recently.

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