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Estimation of Maximum Magnitude (M_{max}): Impending Large Earthquakes in Northeast Region, India

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Abstract: In the present study, the cumulative seismic energy released by earthquakes ($M_w \geq 5$) for a period of 1897 to 2009 is analyzed for northeast (NE) India. For this purpose, a homogenized earthquake catalogue in moment magnitude (M_w) has been prepared. Based on the geology, tectonics and seismicity, the study region is divided into three source zones namely, 1: Arakan-Yoma Zone (AYZ), 2: Himalayan Zone (HZ) and 3: Shillong Plateau Zone (SPZ). The maximum magnitude (M_{max}) for each source zone is estimated using Tsuboi's energy blocked model. As per the energy blocked model, the supply of energy for potential earthquakes in an area is remarkably uniform with respect to time and the difference between the supply energy and cumulative energy released for a span of time, is a good indicator of energy blocked and can be utilized for the estimation of maximum magnitude (M_{max}) earthquakes. The proposed process provides a more consistent model of gradual accumulation of strain and non-uniform release through large earthquakes can be applied in the assessment of seismic hazard. Energy blocked for source zone 1, zone 2 and zone 3 regions is 1.35×10^{17} Joules, 4.25×10^{17} Joules and 7.25×10^{17} Joules respectively and will act as a supply for potential earthquakes in due course of time. The estimated M_{max} for each source zone AYZ, HZ, and SPZ are 8.2, 8.6, and 8.7 respectively. M_{max} obtained from this model is well comparable with the results of previous workers from NE region.

Keywords: Source Zones, Seismic Hazard Assessment, Energy Blocked Model, M_{max}, Northeast India.

INTRODUCTION

Earthquakes are one of the most devastating natural phenomena. Although it is difficult to prevent their occurrence, seismic hazard assessments of the region of interest can be done in order to reduce loss of life, injuries and damages of properties. Keeping in mind the damage ability of the most recent devastating earthquakes like India-Nepal border earthquake of 18 September, 2011 (M_w 6.9), the east coast of Honshu, Japan Earthquake of 11 March, 2011 (M_w 9.0), the Darfield, New Zealand earthquake of September 3, 2010 (M_w 7.0), Hatii earthquake of 12 January 2010 (M_w 7.1), Chile earthquake of 27 February 2010 (M_w 8.8), it is imperative to assess the damage potential of the earthquake in a particular region. Recently, Bilham et al. (2001) argued that any segment of the Himalaya region is presently ready for generating a great earthquake based on the difference between energy accumulation in this region, historical earthquake occurrence and the recent geodetic data. In the recent past, the occurrence of potential earthquakes in the Indian subcontinent reminds us to estimate the hazard for different source zones, to develop the effective strategies and polices to reduce seismic risk and to mitigate earthquake disasters.

The present study includes the northeastern India (NE), which is known for its high level of seismicity and complex tectonic activities. Since 1897, the NE India region has been affected by about 20 large earthquakes ($M > 7.0$). It causes huge loss of lives and properties in the Indian subcontinent. It lies in the highest level of Seismic Hazard Potential Zone V (BIS, IS: (Part 1), 2002) and high seismic risk with PGA value 0.35g to 0.4g (GSHAP) (Bhatia et al.1999). The seismic scenario and amount of loss incurred to human life and property due to earthquakes reveals that the NE Indian region is a tectonically active region with high frequency of earthquake occurrence. Hence, the seismic hazard assessment in terms of estimation of maximum earthquakes (M_{max}) in this region is necessary.

In the present study, the maximum magnitude earthquakes have been estimated using Tsuboi's energy blocked model (Tsuboi, 1964, 1965) for three different major seismotectonics units of NE India. This method requires a homogeneous and complete earthquake catalogue ($M_w \geq 5$) for the study region. The estimation of maximum magnitude

(M_{max}) earthquake is one of the fundamental parameter for seismic hazard assessment of any region. M_{max} is defined as the one that is assessed as physically capable of occurring within a defined seismic regime in an underlying tectonic setup (Thenhaus and Campbell, 2003). Many researchers have observed that occurrence of large earthquakes in the past is evident for the future large earthquakes in a region (Mogi, 1985; Fedotov, 1965; Rikitake, 1976). The seismic hazard assessment in the northeast Indian region has been carried out by others (Shanker and Sharma, 1998; Parvez and Ram, 1999; Shanker and Papadimitriou, 2004; Tripathi, 2006; Mohanty and Walling 2008a, 2008b; Thingbaijam and Nath, 2008; Walling and Mohanty 2009).

On the basis of the Tsuboi's energy blocked model, the supply of energy for potential earthquakes in an area are remarkably uniform with respect to time. The difference between the supply energy and cumulative energy released for a span of time is a good indicator of energy blocked and can be utilized for the estimation of major earthquakes in NE India. Several researchers globally have estimated maximum magnitude using different methods for the different regions of the world, some of them are Main et al. (1999), Pisarenko and Sorenette (2004), Stein and Hanks (1998), Field et al. (1999) and many more. Authors of the above studies have tried to relate the value of M_{max} with the strain rate or the rate of seismic moment release. Other researchers like Kijko (2004) and Mohanty and Walling (2008a) have explained at length about the relationship that takes care of both the extreme and the complete part of the catalogue to calculate the maximum magnitude M_{max}.

REGIONAL SEISMO-TECTONICS OF THE STUDY REGION

The present study region, NE India (Fig.1), lies between 20ºN and 30ºN latitudes and 85ºE and 97ºE longitudes. The significant tectonic features of this region are the eastern Himalaya, the Shillong plateau and the Mikri hills, the Arakan-Yoma subduction zone, and the Brahamaputra valley (Bilham and England, 2001; Kayal et al. 2012). The complex Himalayan structure consists of the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), Main Frontal Thrust (MFT) and their subsidiary thrusts, faults, folds and minor lineaments.

EARTHQUAKE DATABASE

A homogenous and complete earthquake catalogue is

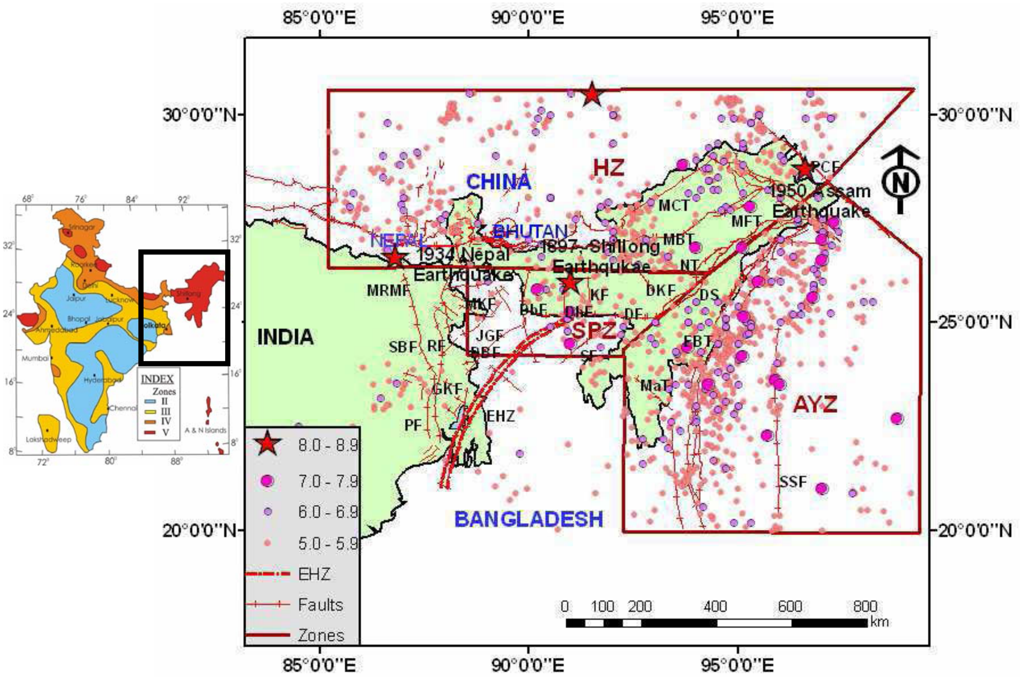

Fig. 1. Tectonic set up of the Northeast (NE) India. MKF: Malda-Kishanganj Fault; DF: Dhubri Fault; JGF: Jangipur-Gaibandha Fault; RF: Rajmahal Fault; SBF: Sainthia Bahmani Fault; GKF: Garhmayna-Khandaghosh Fault; DBF: Debagram-Bogra Fault; PF: Pingla Fault; EHZ: Eocene Hinge Zone; MCT: Main Central Thrust; MBT: Main Boundary Thrust; MFT: Main Frontal Thrust; PCF: Po Chu Fault; NT: Naga Thrust; DT: Disang Thrust; DF: Dauki Fault; KF: Kulsi Fault; DhF: Dudhnoi Fault; SF: Sylhet Fault; LT: Lohit Thrust; DKF: Dhansiri Kopili Fault; MT: Mishmi Thrust; KNF: Katihar-Nailphamari Fault; TF: Tista Fault; MaT: Mat Fault; SSF: Shan-Shagaing Fault; EBTZ: Eastern Boundary Thrust Zone; MRMF: Munger-Saharsha Ridge Marginal Fault (modified after GSI 2000).

one of the essential requirements for seismic hazard analysis of any region. Accordingly, a homogenous and complete earthquake catalogue for a period from 1897 to 2009 has been prepared from different sources like United States Geological Survey (USGS), International Seismological Centre (ISC), Global Centroid-Moment-Tensor (GCMT), Indian Meteorological department (IMD), Bapat et al. (1983) and Chandra (1992) to estimate energy released in the present investigation. The different agencies have reported the earthquake on different scales of magnitude. The moment magnitude (M_w) scale is the most appropriate and widely used magnitude (Kanamori, 1977; Hanks and Kanamori, 1979), as it does not get saturated at higher magnitudes. Different magnitude scales have been converted to a common magnitude M_w using the conversion relationship of Scordilis (2006) and Hanks and Kanamori (1979). Reported intensity data are converted into magnitude using empirical relation M_w = (2/3 MMI+1). Aftershocks and foreshocks have been removed from the catalogue using the declustering approach introduced by Gardner and Knopoff (1974). The final earthquake catalogue is shown in Fig.1. As the energy released by the lower magnitude earthquakes are negligible, the cut off magnitude for the present study is taken as $M_w = 5$.

SOURCE ZONES

To assess the seismic hazard of a region, the first step is to identify the possible sources of seismic activities that are capable of generating future ground motion. Identification of seismic source zones involves the study of tectonic evidences, fault activities and historical and recent seismicity.

On the basis of foregoing description of tectonic features and correlation with past seismicity, three major possible seismic zones in NE India are identified as shown in Fig. 1 (Mohanty and Walling, 2008a; 2008b). These major source zones have been outlined on the basis of three fundamental parameters such as the geology, tectonics, and seismicity. The classification of three zones is as follows.

Zone 1: Arakan-Yoma zone (AYZ),
Zone 2: Himalayan zone (HZ) and
Zone 3: Shillong Plateau zone (SPZ).

The above mentioned zones are described in detail and the hazard parameters are clearly illustrated by Mohanty and Walling (2008a, 2008b). Note that the estimation of hazard parameters may vary depending on the selection of the areal source.

From the observed seismicity, it can be seen that Zone 1 and Zone 2 reveal dense clustering of earthquakes which represent the subduction boundary of the Indian plate under Eurasian plate, and hence there is continuous accumulation of stress.

METHODOLOGY

In this study, energy block model, first introduced by Tsuboi (1964, 1965) in Japan, has been used to further estimate maximum magnitude in the source zones. Energy blocked model reflects the supply of energy for potential earthquakes in an area, which is remarkably uniform with respect to time and the difference between the supply energy and cumulative energy released for a span of time. This model can be utilized for the estimation of maximum magnitude (M_{max}) earthquakes for impending large earthquakes in NE India. The proposed procedure provides a more consistent model of gradual accumulation of strain and non-uniform release through large earthquakes. This model is based on assumption of constant tectonic stress accumulation rate and association of stress blocked with sequence of earthquakes. In Fig.2, the flowchart depicts the steps of the energy blocked model for maximum magnitude analysis in the present study.

The occurrence of earthquakes in an area looks irregular and random if the individual events in a sequence of earthquake events are considered. The cumulative seismic energy released by major earthquakes during the period from 1897 to 2009 in all the zones are calculated and plotted. The plot gives characteristic curve for each zone. The maximum earthquake energy available at a particular time in a given area is given by S, i.e., the upper boundary, and S' is the lower boundary of energy released by an earthquake. The difference between the theoretical upper limit given by S and the cumulative energy released up to that time is

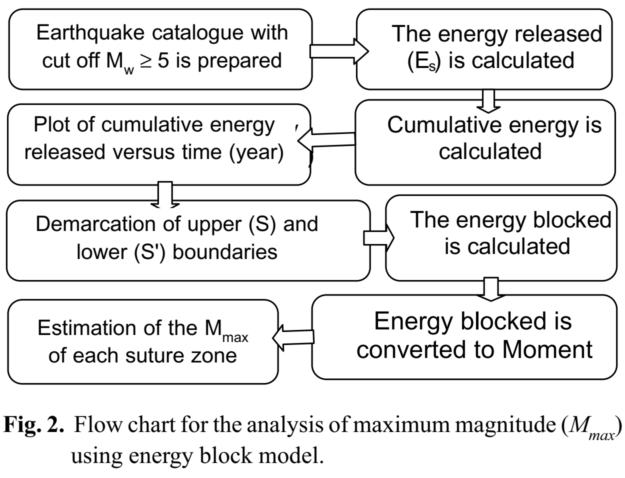

Fig. 2. Flow chart for the analysis of maximum magnitude (M_{max}) using energy block model.

calculated to find out the maximum magnitude of an earthquake which can occur in future.

Time versus energy release is plotted to calculate the energy difference for each event in the study area. It also calculates the maximum possible magnitude earthquake that can occur in the area from the difference in energy of S and energy released by the earthquakes from the earthquake data set. The energy released is calculated using the following relationship suggested by Gutenberg and Richter, (1956). The relationship between the released seismic strain energy (E_S) and surface magnitude (*Ms*) are as follows:

$$\text{Log } E_s = 4.8 + 1.5\, M_s \tag{1}$$

Equation 1, follows:

$$\text{Log } M_o = 1.5\, M_s + 9.1. \tag{2}$$

Resolving equation (2) for the magnitudes one gets the following relation (Kanamori 1977) as:

$$M_W = \frac{2}{3} Log\, M_0 - 6.07 \tag{3}$$

Further the equation (1) is used to resolve M_s and calling it energy magnitude M_E one gets

$$M_E = \frac{2}{3} Log\, E_S - 3.2 \tag{4}$$

and with Kanamori's condition (1977).

According to Kostrov (1974) the radiated seismic strain energy is directly proportional to the stress drop $\Delta\sigma$, namely $Es \approx \Delta\sigma.D.A/2$. From the M_0 definition one can write $Es \approx (\Delta\sigma/2\mu)\, M_0$. Assuming a value for the shear modulus μ in the brittle earth crust and upper mantle (about 3-6× 10^4 MPa) and taking into account that according to Kanamori and Anderson (1975) the stress drop of large earthquakes is constant, ranging between about 2 and 6 MPa, and one gets an average $E_s \approx 5M_0 \times 10^{-5}$. The value of $E_s \approx 5M_0 \times 10^{-5}$ follows the formula

$$M_E = \frac{2}{3} Log\, M_0 - 6.0 = M_W \tag{5}$$

Using the equation (1), the energy released E_s is estimated. The amount of energy blocked in each zone of the NE India is calculated from the energy plots using Tsuboi's model. The energy calculated is in SI units Joules (*J*) = Newton-meter (Nm).

The magnitude for the present study is taken as $M_w \geq 5$, which is not facing the problems of earthquake completeness of historical data. The three seismic zones in NE India; Zone 1: Arakan-Yoma Zone (AYZ), Zone 2: Himalayan Zone (HZ) and Zone 3: Shillong Plateau Zone (SPZ) are taken for estimation of energy blocked using Tsuboi's energy blocked model.

RESULTS

The estimated values of cumulative energy released and energy trapped in terms of M_{max} of each source zone are shown in the Figs. 3 (a), (b) and (c), and in Table 1, respectively. Figure 3(a) shows blocked energy 1.35×10^{17} Joules of Arakan-Yoma zone (AYZ), Figure 3(b) shows blocked energy 4.25×10^{17} Joules of Himalayan zone (HZ) and Figure 3(c) shows blocked energy 7.25×10^{17} Joules of Shillong Plateau zone (SPZ), as a supply for potential earthquakes in future. The Tsuboi's energy blocked model gives the result of the M_{max} from the maximum strain energy trapped in each zone of NE India. Tsuboi (1964) discusses about the uncertainty associated with the energy accumulation estimation, where it is mentioned that the error level on estimated numerical value is not very significant. The maximum magnitude obtained for each source zone AYZ, HZ and SPZ is 8.2, 8.6 and 8.7, respectively. The maximum magnitude earthquakes, M_{max} that can occur in each zone, deduced from energy plots are shown in Table 1.

The results depict that the Shillong plateau zone has the potential for generating highest magnitude earthquake compared to other two zones. The Himalayan zone is experiencing a period of accumulating strain energy at present. The magnitude wise frequency distributions of earthquake occurrences in three seismic source zones from 1897 to 2009 are presented in Table 2. For the comparison of the occurrence of earthquakes in the zones with the forecasted M_{max}, the Table 2 shows statistics of occurrence of earthquakes in the past.

Table 1. The maximum magnitude earthquake that can occur in each zone deduced from energy plots are as followed

Seismic Source Zones	Blocked Energy (in Joules)	Magnitude (M_w)
Arakan-Yoma Zone (AYZ)	1.35×10^{17}	8.2
Himalayan Zone (HZ)	4.25×10^{17}	8.6
Shillong Plateau Zone (SPZ)	7.25×10^{17}	8.7

Table 2. Magnitude wise frequency distribution of earthquake occurrence in the different zones (for the period, 1897–2009)

Seismic Source Zones	M_w: 5–5.9	M_w: 6–6.9	M_w: 7–7.9	M_w: 8–8.9
AYZ	783	100	14	0
HZ	539	118	5	3
SPZ	75	13	3	1

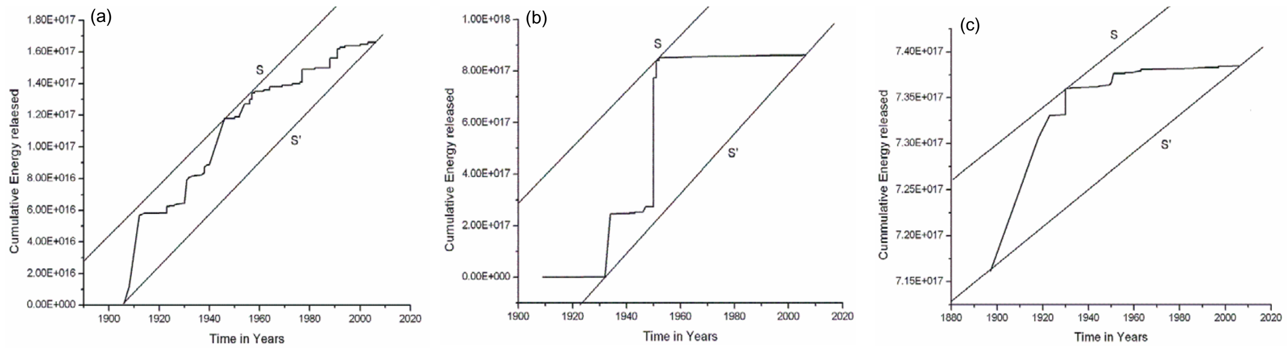

Fig.3. **(a)** shows blocked energy in Arakan-Yoma Zone (AYZ), **(b)** shows in blocked energy in Himalayan Zone (HZ) and **(c)** shows blocked energy in Shillong Plateau Zone (SPZ).

DISCUSSION AND CONCLUSIONS

In the present study, the maximum possible earthquake magnitude for three source zones in NE Indian region are estimated using Tsuboi's energy blocked model. Energy released is calculated for each source zone using the uniform earthquake catalogue in M_w from respective zone.

A plot of time verses cumulative energy released in each source zones is calculated to find out the maximum possible magnitude of earthquake that can occur in each respective zone. The magnitudes of the probable forthcoming earthquakes are found out from the amount of energy which is blocked in each zone of the entire region. The maximum energy trapped in each source zone AYZ, HZ and SPZ are 1.35×10^{17} Joules, 4.25×10^{17} Joules and 7.25×10^{17} Joules respectively, as a supply for potential earthquakes in due course of time. The difference in energy is converted back to its equivalent magnitude in M_w. The maximum magnitude obtained for each source zone 1, 2 and 3, are 8.2, 8.6 and 8.7 respectively. The expected M_{max} is an important parameter for seismic hazard analysis. The calculation of M_{max} has been put forward by different authors in the study region. Mohanty and Walling (2008a) estimated maximum magnitude for zones with a probability of 10% exceedance value in 50 years and reported the M_{max} for zones 1, 2, and 3 as 8.30 ± 0.051, 9.09 ± 0.58 and 9.20 ± 0.51, respectively. The result obtained from the present study is in concurrence with the previous studies. Sankar and Sharma (1998) have estimated the M_{max} 8.5 for NE India using maximum likelihood estimation method. A study by Jade et al. (2007) suggests that there is no significant active deformation within the Shillong Plateau and in the foreland spur north of the plateau in the Brahmaputra valley. It also indicates that the strain energy is continuously being accumulating in the study region. The energy blocked model by Tsuboi (1965) emphasized the gradual accumulation of strain energy and non-uniform release through large earthquakes and can be applied to estimate seismic hazard in any region of interest. It is evident from the present study that the NE India is one of the most vulnerable zones due to earthquake hazards and is experiencing a period of accumulating strain energy at present.

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