

The assessment of seismic hazard in two seismically active regions in Himalayas using deterministic approach

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ABSTRACT

The long stretch of Himalaya is often visited by many major earthquakes from time to time. The work presented in this paper shows the seismic hazard in the northeast Himalayas and the Uttarakhand Himalayas, India. Seismic hazard estimation in these regions is based on the technique given by Joshi & Patel (1997). In this work, the finite rupture along the lineament has been modeled using the semi empirical technique proposed by Midorikawa (1993) and further modified by Joshi & Midorikawa (2005). The modeling procedure follows the ω^2 scaling laws, directivity effects and other strong motion properties.

The NE Himalaya has a complex geology. Seismic activities in this region are due to the trijunction of three mountain belts that are Himalayan range, Mishmi Hills and Naga Patkoi range. The huge oil reservoirs and hydroelectric power projects in this area prove its technoeconomic importance and requirement for detailed seismic hazard assessment. The seismic hazard zonation map for magnitude $M=6$ prepared in this region shows that places like the Tinsukia, North Lakhimpur, Dibrugarh, Ziro, Tezu, Sibsagar, Jorhat, Itanagar, Golaghat, Senapati, Wokha, Imphal and Kohima falls in highly hazardous Zone IV with peak ground acceleration of more than 250 cm/sec^2 . The places like the Daring, Pasighat, Seppa and Basar, region belongs to Zone III with peak ground accelerations of the order 200–250 cm/sec^2 .

The region of Uttarakhand Himalaya has witnessed 13 earthquakes of $M=6$ in last 97 years that indicates the occurrence of one strong earthquake in every 8 years (Rastogi 2000). This region has been visited by two major earthquakes in last one decade. Due to the technoeconomic importance of the region and poor construction practices of building houses, the need for seismic hazard estimation cannot be ruled out in this hilly area. The zonation map prepared for magnitude $M \geq 6.0$ in this region using present technique shows that the places like the Munsiri, Dharchula, Lohaghat, Pithoragarh, Almora, Nainital, Uttarkashi and Karanpryag falls in Zone V with peak ground acceleration of more than 400 cm/sec^2 . The places like Sobla and Gopeshwar lies in Zone IV with peak ground acceleration more than 250 cm/sec^2 . The zonation maps prepared in this work are also compared with the historical past seismicity map of the respective regions and found that many moderate to major earthquakes falls in the identified hazardous zones.

INTRODUCTION

Seismic hazard in an area can be estimated by two approaches (1) Probabilistic seismic hazard assessment approach (PSHA) and (2) Deterministic seismic hazard assessment approach (DSHA). The probabilistic approach uses data of past events in the region while deterministic approach uses geological evidences that can be used for modeling target earthquake. The

requirement of complete past earthquake data is essential for probabilistic seismic hazard assessment technique and in some areas it becomes a difficult task to get complete catalogue. In such conditions the deterministic seismic hazard assessment approach (DSHA) can be better utilized to estimate the seismic hazard in an area.

Seismic zoning can be defined as a process of demarcating or mapping areas of equal seismicity, or

of equal hazard related to a characteristic of strong ground shaking and of site or structural response (Todorovska et al., 1995). The peak ground acceleration is an important strong motion parameter for safe engineering design of the structures. Therefore the zoning based on peak ground acceleration is more useful to predict seismic hazard than the other parameters. The unavailability of strong motion data for different seismically active regions always put hurdle in seismic hazard studies. The alternate approach is the simulation of strong ground motion.

Strong ground motion can be simulated using (1) Composite source modelling technique (Zeng, Anderson & Su 1994; Yu, 1994; Yu et al., 1995; Saikia & Herrman 1985 and Saikia 1993); (2) Stochastic simulation technique (Boore 1983; Boore & Atkinson 1987 and Lai 1982) and (3) Empirical Green function technique (Irikura 1986; Hartzell 1978; 1982; Kanamori 1979; Hadley & Helmberger 1980; Mikumo, Irikura & Imagawa 1981; Irikura & Muramatu, 1982; Irikura 1983, 1986; Kamae & Irikura 1998; Munguia & Brune, 1984 and Hutchings 1985).

The composite source modeling technique is proposed by Zeng, Anderson & Su (1994) and Yu (1994). This technique uses the synthetic Green's function for the generation of synthetic strong-motion seismograms. The source is described with superposition of circular subevents. This technique requires a detailed velocity Q structure of the region; the fault plane solution and the stress drop parameters. Value of these parameters is difficult to interpret at the site of interest. In the stochastic simulation technique a band limited random white Gaussian noise is passed through number of filters representing earthquake process to get a synthetic ground motion (Housner & Jennings 1964; Hanks & McGuire 1981; Boore 1983; McGuire, Becker & Donovan 1984; Boore & Joyner 1991; Shinozuka & Sato 1967 and Lai 1982). This method is based on point source assumption and it is well known that this assumption fails at near source region of large earthquakes. Hartzell (1978) and Irikura (1986) have proposed empirical green function (EGF) technique in which the source has been considered of finite length, downward extension and has been divided into small elements. Each element has been representing the small earthquake. The small earthquake needed in this technique should be located ideally near the source and recorded at a site for which a large event simulation is desired (Joyner and Boore 1988). This is the most difficult condition to be met when applying this method and hence it is of limited use. Midorikawa (1993) has proposed a semi-empirical technique based on the empirical green function

technique of Irikura (1986) in which the small earthquake used in the empirical green function technique has been replaced by time series having envelope of accelerograms in time domain and spectral contents of high frequency accelerograms in the frequency domain. This technique has been successfully tested by Midorikawa (1993) on 1985, Central Chile earthquake. This semi empirical technique has been further modified for layered earth model by Joshi, Singh & Kavita. (2001). Although all the above mentioned techniques have their own advantages as well as disadvantages yet the semi empirical approach is the simplest approach as it is based on the simple empirical formulas and it does not require small earthquakes in the source region as required in EGF technique.

Based on the technique of Midorikawa (1993), Joshi & Patel (1997), has proposed a method of seismic hazard estimation. In this method, the seismic hazard zonation map has been produced using the semi empirical modeling technique proposed by Midorikawa (1993). The work presented in this paper covers the estimation and comparison of seismic hazard based on peak ground acceleration in seismically two very active parts of Himalaya, (i) the Uttarakhand Himalaya with latitude 29° -33°N and longitude 78°-81°E and (ii) Northeastern region of India with latitude 24° - 29°N and longitude 93°-97°E by using the seismic hazard estimation technique proposed by Joshi & Patel (1997).

METHODOLOGY

The work presented in this paper discussed the application of peak ground acceleration parameter in preparation of seismic zonation map of any area. For the computation of peak ground acceleration the rupture length along identified lineament has been modeled using semi empirical approach of Midorikawa (1993). The algorithm of seismic zonation has been given in Fig.1 and the method of seismic zonation adopted in the present work in step wise manner has been given below (after Joshi and Patel, 1997 and Joshi, Kapil Mohan & Patel 2007):

(i) The identification of active lineaments is the first step in this approach. Active lineaments can be identified from geological information, satellite imageries and fieldwork. For modeling of earthquake along these lineaments we require rupture length (L) which is measured from the map of identified active lineaments. To calculate the magnitude from the length of the lineament, the relationship of Araya & Kiureghian (1988) has been used. Using the relationship of Kanamori and Anderson (1975), the

ruptured area (A) is calculated assuming the rectangular rupture model. This area is used to compute the width (D) of the rupture plane i.e., $D = A/L$. The values of parameters L , D , L_e (length of the small event) and D_e (downward extension of small event) for each rupture model are computed from applicable empirical relations and similarity relationship. The magnitude of the elementary earthquake depends upon the scaling laws used in the studied region.

(ii) In order to obtain value of peak ground acceleration at different part of the region, the entire region is divided into square grids of equal sizes. The observation points are located in the corner of these grids.

(iii) At each observation point peak accelerations are computed by modeling the rupture along each identified lineament. The process of modeling of one such rupture has been shown in Fig.2. The rupture

along each identified lineaments have been modeled using semi empirical approach of Midorikawa (1993). For 'n' number of lineaments 'n' values of peak accelerations i.e., $P_{a1}, P_{a2}, \dots, P_{an}$ are obtained at that observation point. A new parameter ' E_{PGA} ' is introduced which is defined as the maximum peak acceleration experienced at a particular site by earthquake of different magnitudes (Joshi & Patel 1997):

$$E_{PGA} = \text{Max} \{P_{a1}, P_{a2}, \dots, P_{an}\}$$

Where P_{a1}, P_{a2}, \dots are the peak ground accelerations at a particular site.

Hence E_{PGA} gives the information about maximum peak ground acceleration any point can experience due to activation of rupture along identified lineaments.

(iv) This process is repeated at all observation points to obtain the distribution of expected peak ground acceleration (E_{PGA}) in the region. The contours of the expected acceleration have been used for defining various zones.

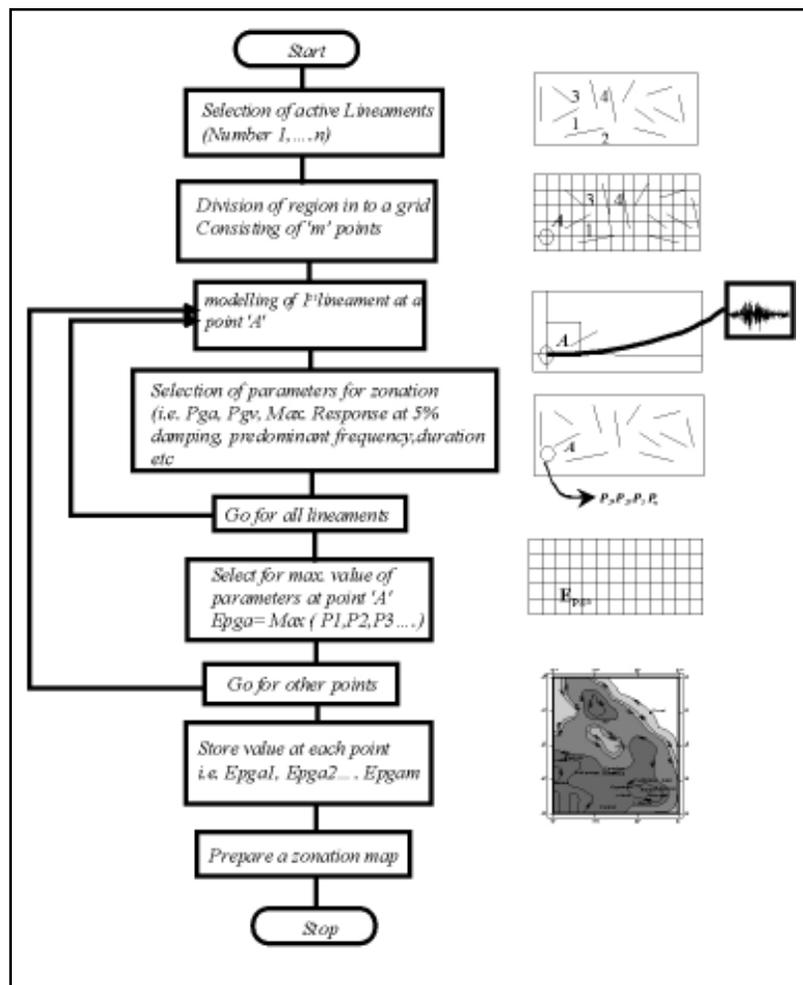


Figure 1. Algorithm for the preparation of seismic zonation map.

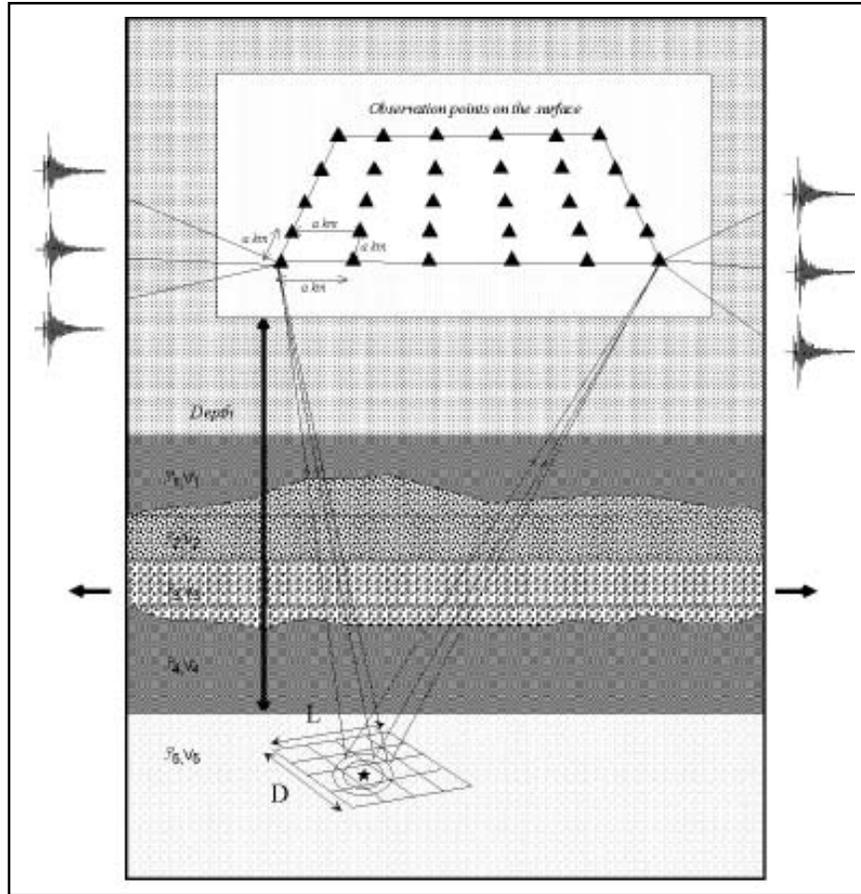


Figure 2. The pictorial presentation of the methodology adopted for the estimation of peak ground acceleration in the present work.

SCALING LAWS IN THE REGION

The methodology of the present work requires various regression relations. Before using these regression relations their applicability needs to be checked. In their study to check the applicability of regression relation for the Uttarakhand Himalaya and Northeastern region, Joshi (2004) and Joshi, Kapil Mohan & Patel (2007) have tested various regression relations related to peak ground acceleration. It was found that the minimum root mean square error (RMSE) was obtained when the relation of Abrahamson & Litehiser (1989) is used. We have used the same tested attenuation relation in this study.

Another parameter used in the envelope function is the duration parameter. The duration parameter defined by Midorikawa (1993) represents the arrival time of peak in the acceleration envelope and in the present work following relation modified by Joshi (2004) for its applicability for Himalayan earthquake has been used:

$$d_{ij} = .0015 10^{0.2M} + .16R^{0.6} \dots\dots (1)$$

Where M is the surface wave magnitude and R is the

hypocentral distance and d_{ij} is the duration parameter in sec.

Strong motion records shows strong directivity effects, which depends on the mode of rupture propagation. Regression relations do not account such effects. The directivity effect has been verified in the semi-empirical modeling technique by Joshi and Midorikawa (2005) and has been presented in detail by Joshi & Patel (1997). The prepared zonation map using this technique is strongly dependent on the location of modeled rupture plane and its orientation. Such study has been discussed in detail by Joshi, Kapil Mohan & Patel (2007).

ZONATION MAP FOR NORTHEASTERN INDIA

The NE Himalaya has a complex geology. Seismic activities in this region are due to the trijunction of three mountain belts that are Himalayan range, Mishmi Hills and Naga Patkoi range. Active faults and seismicity in the Himalaya are expression of recent and subrecent crustal movements due to ongoing continental collision

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(Valdiya 1980; Karunakaran & Ranga Rao 1979).

Based on the study of satellite imageries, tectonic features and geological formations, GSI (2000) has published a detail seismotectonic map in the Northeast part of India. The same map has been used in this study (Fig.3). Total 104 lineaments have been selected from this map which can generate a magnitude $M > 6$ earthquake. The magnitude of modeled earthquake has been calculated by empirical relationship between length of the lineament and magnitude proposed by Araya & Kiureghian (1988). In this study the rectangular rupture plane has been considered. The area of the rupture plane has been calculated by empirical relationship given by Kanamori & Anderson (1975). Assuming the magnitude of an elementary earthquake as 5.8, the values of parameters L_c and D_c (length and downward extension of the small element earthquake respectively) for each rupture model are computed from self similarity relationship proposed by Kanamori & Anderson

(1975). The parameter like strike of rupture plane is measured from the tectonic map whereas the dip of modeled rupture plane is assumed as 60° . The rupture velocity has been taken as 2.7 km/sec. The velocity model proposed by Mukhopadhyay, Chander & Khattri. (1997) has been considered in the present study (Table 1).

Table 1. Velocity model used for Northeast part of India (After Mukhopadhyay, Chander & Khattri1997).

Depth to the top of the layer (km)	Velocity V_s (km/sec)
0.0	2.3
1.0	3.3
25.0	3.9
45.0	4.7

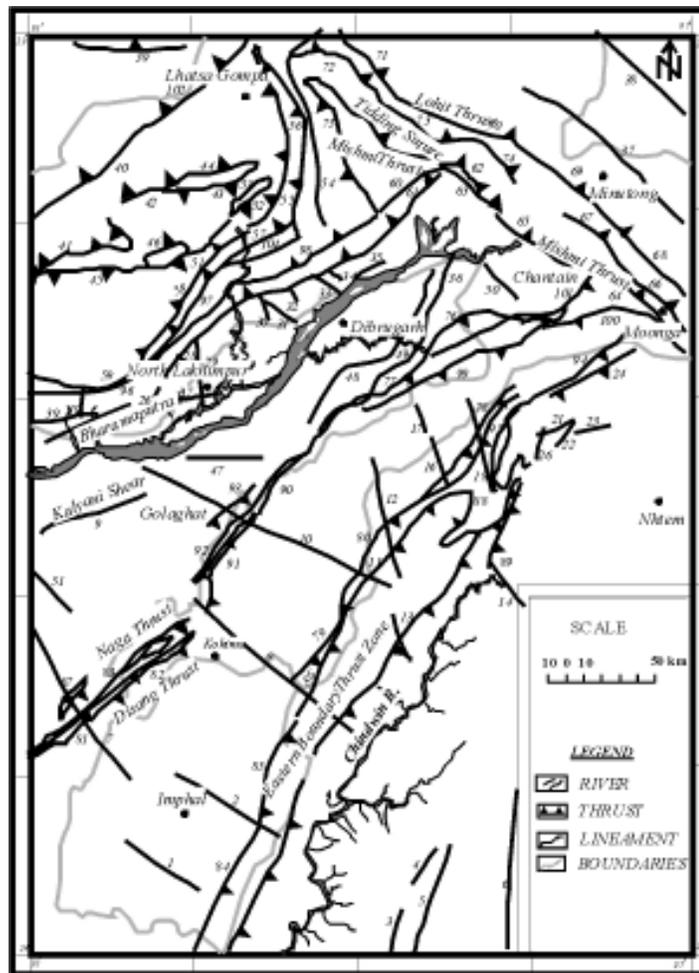


Figure 3. Tectonic map of the Brahmaputra valley showing various lineaments (Modified after GSI. 2000). The lineaments are marked by numbers for modeling purpose.

The entire area of study has been divided into 99 square grids each of length 50 km and each corner of grids are assumed as observation point. By modeling all 104 lineaments, expected peak ground acceleration is calculated at all observation points. The value of E_{pga} at each observation point is used for the preparation of a contour map. On the basis of E_{pga} values, the entire region has been divided into different zones. Bureau of Indian Standard (BIS), Govt. of India has divided entire Indian subcontinent in to four zones on the basis of expected peak ground acceleration (BIS 2002). Similar range in peak ground acceleration has been used in the present work to

divide the Northeastern India into different seismic zones. This zonation map has been shown in Fig.4.

The zonation map prepared using current technique indicates that entire Brahmaputra valley falls in the area prone to high seismic hazard. The places like Tezu, Dibrugarh, Tinsukia, Ziro, North Lakhimpur, Sibsagar, Itanagar, Jorhat, Golaghat, Senapati, Wokha, Imphal and Kohima experiences a peak ground acceleration of more than 250 cm/sec^2 . The other important locations in this region like Pasighat, Dimapur, Daring, Basar, Seppa and Mon falls in zone III with peak ground acceleration of the order of 200 to 250 cm/sec^2 .

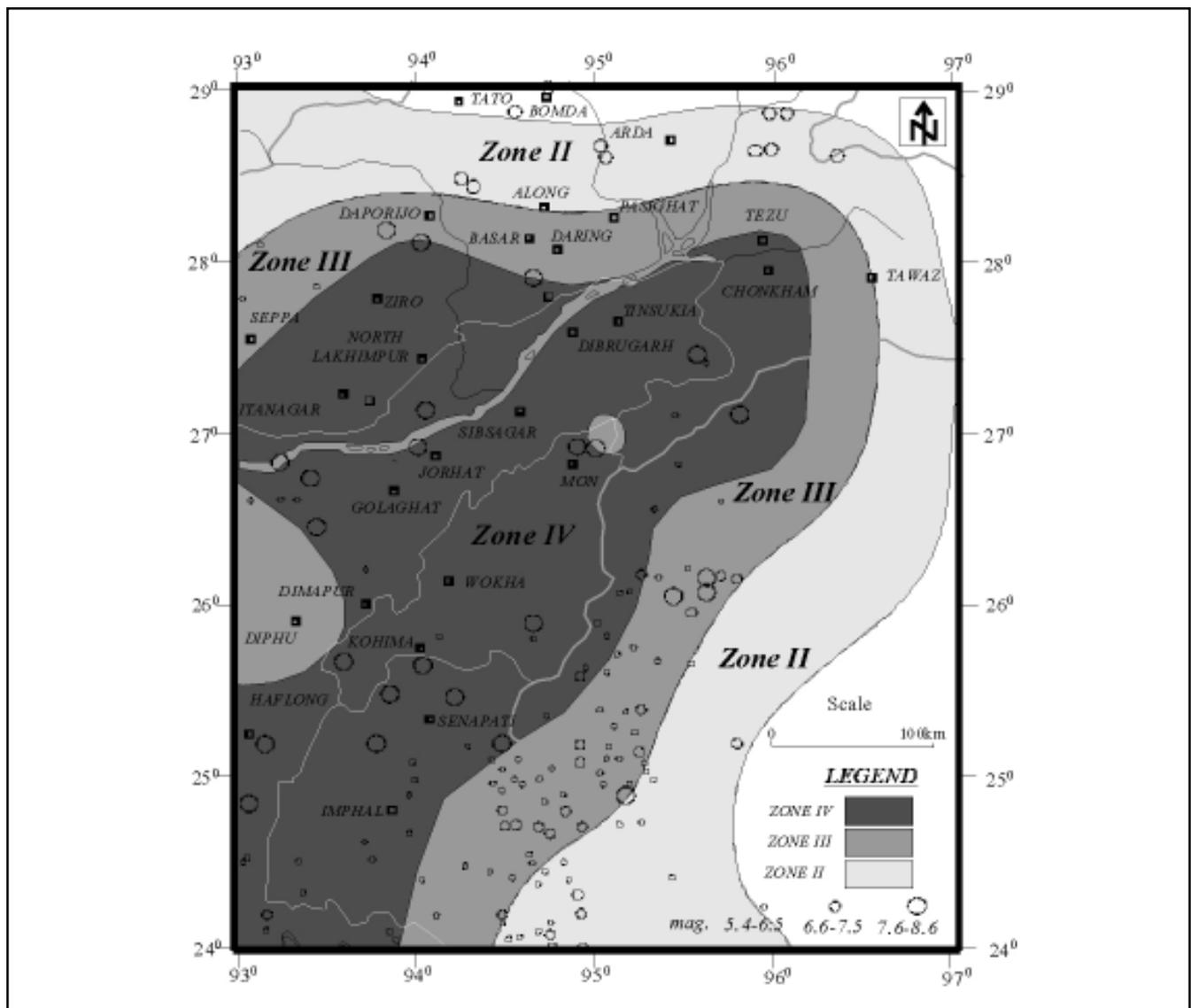


Figure 4. Seismic Hazard zonation map of Northeastern region of India. In this map zone IV stands for $250 \leq E_{pga} < 400 \text{ cm/sec}^2$ zone III consist of $200 \leq E_{pga} < 250 \text{ cm/sec}^2$ and zone II has $100 \leq E_{pga} < 200 \text{ cm/sec}^2$. Epicenters of past earthquakes are taken from Nagarajan (2001).

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CASE STUDY:

Zonation map in Uttarakhand Himalaya

The region of Uttarakhand Himalaya has witnessed 13 earthquakes of $M > 6$ in last 97 years this indicates the occurrence of one strong earthquake in every 8 years (Rastogi 2000). This region has been visited by two major earthquakes in last one decade. The 91.5% houses in the Uttarakhand state are made up of mud and adobe, burnt brick and stones and are weakest in strength during earthquake (Arya 1995). Few hydroelectric projects are also running in the state. Due to the techno-economic importance of the region and poor construction practices of building houses, the need for seismic hazard estimation cannot be ruled out in this hilly area.

The knowledge of active lineaments is a necessary requirement for the preparation of zonation map using the approach of Joshi & Patel (1997) and Joshi et al. (2007). Based on the study of satellite imageries,

tectonic features and geological formations GSI (2000) has published a detail seismotectonic map in this area (Fig.5). From this tectonic map 67 lineaments have been selected which can give rise to a magnitude $M > 6.0$ earthquake. These are marked by numbers as shown in Fig.5. Based on regression relation of rupture length and magnitude, the maximum magnitude of modeled earthquake is 7.9 (M_s) in this region. The average depth of detachment in this region is 12 km and study of the Uttarkashi (1991) and the Chamoli (1999) earthquakes has shown that the rupture causing these earthquakes have been originated at the detachment. Due to this reason we have modeled the rupture causing earthquakes in this region at the depth of 12 km. The parameter like strike of rupture is measured from the tectonic map whereas the dip of modeled rupture plane is assumed as 15° . Assuming the magnitude of an elementary earthquake as 4.8, the values of parameters L , D , L_c and D_c for each rupture model are computed from self similarity relationships proposed by Kanamori & Anderson (1975).

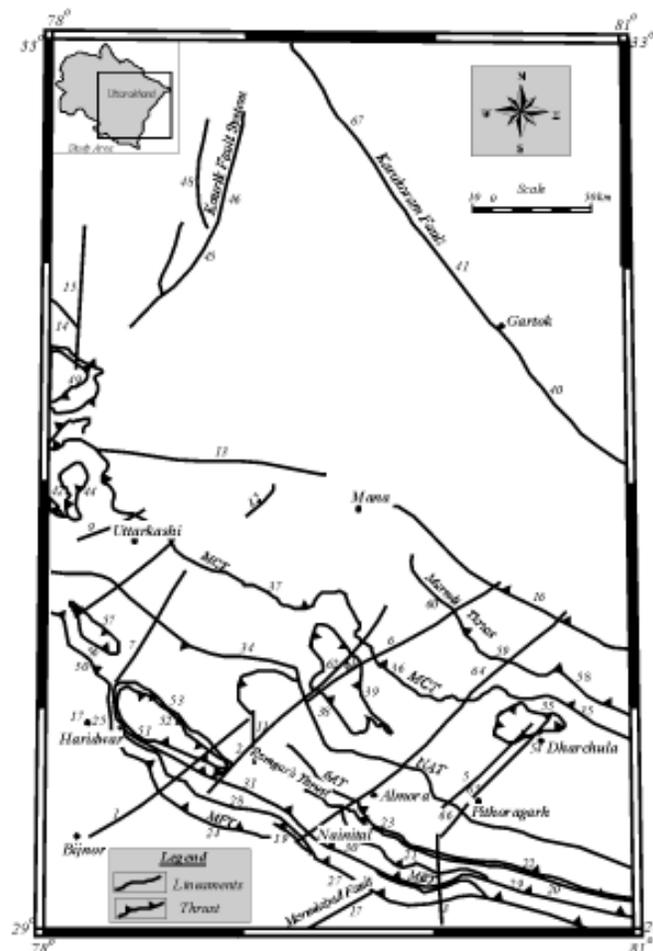


Figure 5. Tectonic map of the Uttarakhand Himalaya showing various lineaments (Modified after GSI 2000). The lineaments are marked by numbers for modeling purpose.

The rupture velocity is assumed as 2.6 km/sec and this is 80% of S wave velocity (Mendoza & Hartzell 1988).The velocity structure used in the present work has been taken after Yu et al., (1995) and given in Table 2.

Table 2. Velocity model used in the Uttarakhand Himalaya (after Yu et al., 1995).

Depth to the top of the layer (km)	Velocity V_s (km/sec)
0.4	2.0
1.0	2.86
15.0	2.60

The entire region is divided into 63 (7x9) square grids of length 50 km and each corner of grids are assumed as observation point. By modeling each 67 lineaments, expected peak ground acceleration is calculated at all observation points. The value of E_{pga} at each observation point is used for the preparation of a contour map.

The seismic zonation map for Uttarakhand Himalaya shows that Dharchula, Pithoragarh, Almora, Haridwar, Okhimath, Uttarkashi and Karnprayag regions fall in zone V where they can experience peak ground acceleration of order more than 400 cm/sec^2 . The other important locations in this region like Sobla and Gopeshwar fall in zone IV where they can experience the peak ground acceleration of the order of 250 to 400 cm/sec^2 .

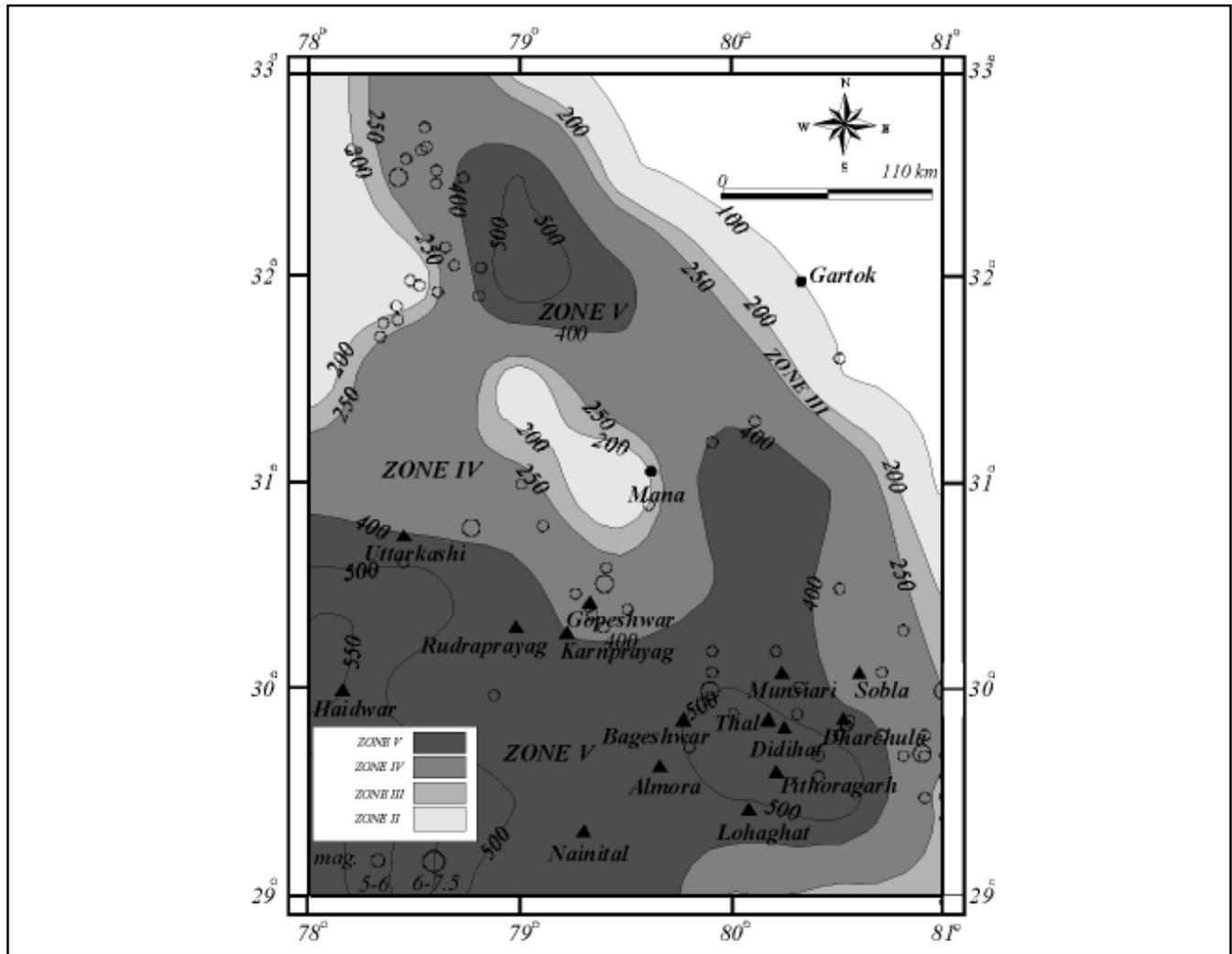


Figure 6. Seismic zonation map of Uttarakhand Himalaya. In this map zone V stand for $E_{pga} > 400 \text{ cm/sec}^2$, zone IV for $250 \leq E_{pga} < 400 \text{ cm/sec}^2$, zone III for $200 \leq E_{pga} < 250 \text{ cm/sec}^2$ and zone II stands for $100 \leq E_{pga} < 200 \text{ cm/sec}^2$. Epicenters of earthquakes are taken from USGS.

DISCUSSION

In the present work the seismic hazard maps of Northeast Himalaya and Uttarakhand Himalaya have been prepared using the methodology given by Joshi & Patel (1997) and Joshi, Kapil Mohan & Patel. (2007). These seismic hazard maps for northeast part of India and Uttarakhand Himalaya are shown in Fig 3 and Fig 5 respectively. On the basis of identified active lineaments, maximum earthquake modeled in NE and Uttarakhand Himalaya are 7.6 and 7.9 (Ms), respectively. The area in these maps has been divided in different zones on the basis of expected peak ground acceleration. These zones follow the similar range of peak ground acceleration as proposed by Bureau of Indian standard map (BIS 2002). In zone wise scenario, an area of 55000 km² falls in highly hazardous zone V in the Uttarakhand Himalaya. However the prepared zonation map for NE Himalaya shows that region does not have any area under zone V. The area covered by Zone IV in the hazard map of NE Himalaya is approx. 95000 km², whereas an area of approximately 46000 km² is covered by IV in the zonation map prepared for Uttarakhand Himalaya. The area covered under zone III in the zonation map prepared for NE Himalaya is approximately 55000 km²; however in Uttarakhand Himalaya it is of the order of 8500 km² only. The same scenario of proportionality in zone area is also seen in zone II where 60,000 km² of the area is covered by zone II in the hazard map for northeast India; however the area of 15000 km² has been covered in zone II in the hazard map prepared for the Uttarakhand Himalaya.

In this study the maximum peak ground acceleration of the order of 550 cm/sec² and 350 cm/sec² have been observed in the Uttarakhand and northeast Himalaya respectively. The expected peak ground acceleration is higher in the Uttarakhand Himalaya as compared to the NE Himalaya. This may be due to the selection of different modeling parameters based on past seismicity, geology and tectonics in these two regions. The depth of the rupture plane is very important parameter in modeling of ground motion. In Uttarakhand Himalaya the past seismicity is concentrated at low depth (10 to 15 km) below the surface of earth whereas in the study area selected in Northeast part of India it is concentrated around 30 km of depth.

CONCLUSIONS

This paper present seismic zonation maps for seismically active Uttarakhand and Northeast Himalaya. This study shows that Brahmaputra valley

falls in the area prone to high seismic hazard. The Tezu, Tinsukia, Dibrugarh, Ziro, North Lakhimpur, Itanagar, Sibsagar, Jorhat, Golaghat, Wokha, Senapati, Imphal and Kohima regions falls in the zone where they can experience peak ground acceleration more than 250 cm/sec². The other important locations in this region like Pasighat, Daring, Basar and Seppa falls in zone III which can experience peak ground acceleration of the order of 200 to 250 cm/sec². The seismic zonation map for Uttarakhand Himalaya shows that Dharchula, Pithoragarh, Almora, Haridwar, Okhimath, Uttarkashi and Karnprayag regions fall in zone V where they can experience peak ground acceleration of order more than 400 cm/sec². The other important locations in this region like Sobla and Gopeshwar fall in zone IV where they can experience the peak ground acceleration of the order of 250 to 400 cm/sec². In zone wise scenario, an area of 55000 km² falls in highest zone V in Uttarakhand Himalaya where as around 95000 km² area of Northeast Himalaya falls in zone IV. The current study shows that high expected peak ground acceleration is observed in the Uttarakhand Himalaya and maximum area of Uttarakhand Himalaya falls in highly hazardous zone compared to NE Himalaya.

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REFERENCES

- Abrahamson, N.A. & Litehiser, J.J., 1989. Attenuation of vertical peak acceleration, Bull. Seis. Soc. Am. 79, 549-580.
- Araya, R. & Kiureghian, A.D., 1988. Seismic hazard analysis, improved models, uncertainties and sensitivities; Report no. EERC-90/11, Earthquake Engineering Research Center, University of California, Berkeley, C.A. 155pp.
- Arya, A.S., 1995. Long term measures for earthquake protection in Uttaranchal area of Uttar Pradesh, India, Mem. Geol. Soc. of India, 30, 191-201.
- BIS, 2002. Indian standards code of practice for earthquake resistant Design of Structures, Indian Standards Institution, New Delhi.
- Boore, D.M., 1983. Stochastic simulation of high frequency ground motion based on seismological models of radiated spectra, Bull. Seism. Soc. Am., 73, 1865-1894.
- Boore, D.M. & C.M., Atkinson, 1987. Stochastic prediction of ground motion and spectral response parameters

- at hard rock sites in eastern North America, *Bull. Seismol. Soc. Am.*, 77, 440-467.
- Boore, D.M. & Joyner, W.B., 1991. Estimation of Ground Motion at Deep Soil Sites in eastern north America, *Bull. Seism. Soc. Am.*, 81, 2167-2185.
- GSI, 2000. Seismotectonic atlas of India and its environs, Geological Survey of India.
- Hadley, D.M. & Helmberger, D.V., 1980. Simulation of strong ground motions, *Bull. Seism. Soc. Am.*, 70, 617-610.
- Hanks, T.C. & McGuire, R.K., 1981. Character of high frequency ground motion, *Bull. Seism. Soc. Am.*, 71, 2071-2095.
- Hartzell, S.H., 1978. Earthquake aftershocks as green functions, *Geophys. Res. Lett.*, 5, 1-4.
- Hartzell, S.H., 1982. Simulation of ground accelerations for May 1980 Mammoth Lakes, California earthquakes, *Bull. Seism. Soc. Am.*, 72, 2381-2387.
- Housner, G.W. & Jennings, P.C., 1964. Generation of Artificial earthquakes, *Proc. ASCE* 90, 113-150.
- Hutchings, L., 1985. Modeling earthquakes with empirical green's functions (abs), *Earthquake Notes* 56, 14pp.
- Irukara, K., 1983. Semi empirical estimation of strong ground motion during large earthquakes, *Bull. of Disaster Prevention Res. Inst.*, 33, 63-104.
- Irikura, K., 1986. Prediction of Strong Acceleration Motion Using Empirical Green's Function, *Proceed. 7th Japan Earthquake Engineering Symposium*, 151-156.
- Irikura, K. and Muramatu, I., 1982. Synthesis of strong ground motions from large earthquakes using observed seismograms of small events *Proc. of 3rd Internat. Microzonation Conf. 1, Seattle*, 447 - 458.
- Joshi, A., 2004. A simplified technique for simulating wide band strong ground motion for two recent Himalaya earthquakes, *Pure & Appl. Geophysics* 161, 1777-1805.
- Joshi, A. & Midorikawa, S., 2005. Attenuation characteristics of ground motion Intensity from earthquakes of intermediate depth, *J. of Seismology* 9, 23-37.
- Joshi, A., Kapil Mohan & Patel, R.C., 2007. A deterministic approach for preparation of seismic hazard maps in North East India, *Natural Hazards*, 43, 129-146.
- Joshi, A. & Patel, R.C., 1997. Modelling of active lineaments for predicting a possible earthquake scenario around Dehradun, Garhwal Himalaya, India, *Tectonophysics* 283, 289-310.
- Joshi, A., Singh, S. & Kavita, G., 2001. The simulation of ground motion using envelope summation, *Pure & Appl. Geophys.* 158, 877-901
- Joyner, W. B. & Boore, D.M., 1988. Measurement, characterization and prediction of strong ground motion, *Proceedings of Earthquake Engineering and Soil Dynamics II, Utah*, June 27-30, 43-100.
- Kamae, K. & Irikura, K., 1998. Source model of the 1995 Hyogo-ken Nanbu earthquake and simulation of near source ground motion, *Bull. Seism. Soc. Am.*, 88, 400-412.
- Karunakaran, C. & Ranga Rao, A., 1979. Status of exploration for hydrocarbons in the Himalayan region . Contributions to stratigraphy and structure. *Him. Geol. Sem, Geol.Surv. India.* 41 (5), 1-68.
- Kanamori, H., 1979. A semi empirical approach to prediction of long period ground motions from great earthquakes, *Bull. Seis. Soc. Am.* 69, 1645-1670.
- Kanamori H. & Anderson, D.L., 1975. Theoretical basis of some empirical relation in seismology; *Bull. Seis. Soc. Am.*, 65, 1073-1095.
- Lai, S.P., 1982. Statistical characterization of strong motions using power density spectral function, *Bull. Seis. Soc. Am.*, 72, 259-274.
- McGuire, R.K., Becker, A.M. & Donovan, N.C., 1984. Spectral estimates of seismic shear waves, *Bull. Seis. Soc. Am.*, 74, 2167-2185.
- Midorikawa, S., 1993. Semi empirical estimation of peak ground acceleration from large earthquakes, *Tectonophysics* 218, 287-295.
- Mikumoto, T., Irikura, K. & Imagawa, K., 1981. Near field strong motion synthesis from foreshock and aftershock records and rupture process of the main shock fault (abs.), *IASPEI 21st General Assembly, London, Canada.*
- Mendoza, C. and Hartzell, S.H., 1998, Inversion for slip distribution using GSDN P waves: North Palm Springs, Borah Peak and Michoacan earthquakes, *Bull. Seismol. Soc. Am.*, 78, 1092-1111.
- Mugua, L. & Brune, J.M., 1984. Simulations of strong ground motions for earthquakes in the Mexicali-Imperial valley; *Proc. of workshop on strong ground motion simulation and earthquake engineering applications Pub. 85- 02 Earthquake Engg. Res. Inst., Los Altos, California*, 21-1-21-19.
- Mukhopadhyay, S., Chander, R. & Khattri, K.N., 1997, Crustal properties in the epicentral tract of the great 1897 Assam Earthquake, northeastern India, *Tectonophysics*, 283, 311-330.
- Nagrajan, R., 2001. Rapid assessment procedure to demarcate areas susceptible to earthquake-induced ground failures for environment management-a case study from parts of northeast India, *Bull. of Engineering geology and the environment*, 61, 99-119.
- Rastogi, B.K., 2000. Chamoli earthquake of magnitude 6.6 on March 1999, *Jour.Geol.Soc.India*, 55, 505-514.
- Saikia, C.K. & Herrmann, R. B., 1985. Application of Waveform Modelling to Determine Focal Mechanisms of Four 1982 Miramichi Aftershocks, *Bull. Seism. Soc. Am.*, 75, 1021-1040.
- Saikia, C.K., 1993. Ground Motion Studies in Great Los

Angles due to $M_w = 7.0$ Earthquake on the Elysian Thrust Fault, Bull. Seism. Soc. Am., 83, 780-810.
Shinozuka, M. & Sato, Y., 1967. Simulation of nonstationary random processes, Proc. ASCE 93, 11-40.
Todorovska, M.I., Gupta, I.D., Gupta, V.K., Lee, V.W. & Trifunac, M.D., 1995, Selected Topics in seismic hazard analysis, Report published in University of South California, Deptt. of civil engineering, no. CE 95-08.
Valdiya, K.S., 1980. Two intra-crustal boundary thrusts of Himalaya, Tectonophysics, 66, 323-348.
Yu, G., Khattri, K.N., Anderson, J.G., Brune, J.N. & Zeng, Y., 1995. Strong ground motion from the Uttarkashi

earthquake, Himalaya, India, Earthquake: Comparison of Observations with Synthetics Using the composite source model, Bull. Seis. Soc. Am., 85, 31-50.

Yu, G., 1994. Some aspects of earthquake seismology: slip portioning along major convergent plate boundaries: Composite source model for estimation of strong motion and non linear soil response modeling, Ph.D. thesis, University of Nevada.
Zeng, Y., Anderson, J.G. & Su, F., 1994. A composite source model for computing realistic synthetic strong ground motions, Geophy. Res. Lett., 21,725-728.

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