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Understanding earthquake disaster in central Himalayas – a perspective of mitigation and hazard prediction

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ABSTRACT

Annually, about 100,000 earthquakes of magnitude more than three hit the earth. As a result, more than 15 million human lives have been lost and damage worth of hundreds of billions of dollars has been inflicted in the recorded history due to these disasters. More than a dozen earthquakes of $M_s > 7.5$ have occurred in the Himalayan region since 1897. The seismic activity in the Himalayan frontal arc is the result of continued collision between the Indian and Eurasian plates.

Most of the earthquake generation models currently used for seismic hazard evaluation are based on the assumption of Poisson or other memoryless distribution, i.e. low-magnitude earthquakes follow the Poisson distribution (random event) and large-magnitude events follow the exponential distribution (non-random). The study suggests that the region has low probabilities and large mean return periods for higher-magnitude earthquakes. The earthquake generation process in Nepal–Central Himalayas supports the time- and magnitude-predictable model, which is valid for $5.5<M_s<8.6$. The analysis suggests that the probability of occurrence of moderate earthquakes ($M_s = 5.8–6.5$) in the next decade in the Central Himalayan region is very high (0.59–0.91), whereas it is very low (<0.40) for southern Tibet.

Keywords: Earthquake, disaster, hazard prediction, mitigation, earthquake generation model

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INTRODUCTION

Earthquakes are nothing but natural energy release driven by the evolutionary processes of the planet we live on. Earthquakes have caused massive destruction to human life and property, where these events have occurred near human settlements. Earthquakes, therefore, are and were thought of as one of the worst enemies of mankind. Due to the very nature of release of energy, damage is evident which, however, will not culminate in a disaster unless it strikes a populated area. The word mitigation may be defined as the reduction in severity of something. The earthquake disaster mitigation, therefore, implies that such measures may be taken, which help reduce severity of damage caused by an earthquake to life, property, and environment. While "earthquake disaster mitigation" usually refers primarily to interventions to strengthen the built environment, and "earthquake protection" is now considered to include human, social, and administrative aspects of reducing earthquake effects. It is not only the basic understanding of the phenomenon of earthquake, its resistance offered by the designed structure, but the understanding of the socio-economic factors, engineering properties of the indigenous materials, local skill, and technology transfer models are also of vital importance. It is important that the engineering aspects of mitigation should be made a part of public policy documents. It should, however, be noted that reduction of earthquake hazards through prediction is considered to be one of the effective measures, and much effort is spent on prediction strategies. While earthquake prediction does not guarantee safety and, even if predicted correctly, the damage to life and property on such a large scale warrants the use of other aspects of mitigation. While earthquake prediction may be of some help, mitigation remains the main focus of attention of the civil society.

Earthquakes are one of the worst among the all natural disasters. About 100,000 earthquakes of magnitude more than three hit the earth every year. According to a conservative estimate more than 15 million human lives have been lost and damage worth of hundreds of billions of dollars has been inflicted in the recorded history due to these disasters. Some of the catastrophic earthquakes of the world are Tangshan of China (1976, $Ma=7.8$, casualty > 300,000), Mexico city (1985, casualty > 10,000), and Northwest Turkey (17 August 1999, $Ma=7.4$, casualty > 20,000). In India, casualty-wise the first three events are Kangra (>20,000), Bihar–Nepal (>10,653), and Killari (>10,000). Moreover, the Indian subcontinent, particularly the Central Himalaya, is one of the most earthquake-prone regions in the world.

Intense seismic activity associated with the Himalayan Frontal arc affects India, Nepal, and Bangladesh. The approximately 2000 km long Himalayan frontal arc (from the Western Syntaxis in Kashmir to the Eastern Syntaxis in Assam) has been seismically very active. More than a dozen earthquakes of $M_s > 7.5$ have occurred in this region since 1897. The seismic activity in the Himalayan frontal arc is the result of continued collision between the Indian and Eurasian plates (Fig. 1). Three fault zones dominate the deformation of the Himalayan frontal arc: the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT). It appears that the tectonic activity has been shifting from the MCT and MBT in the north to the MFT in the south, along which the Indian subcontinent under thrusts beneath the Himalaya (Molnar and Lyon-Caen 1989).

The Indian plate is subducting under the Tibetan plate with a displacement ≥ 2 cm/year. Such a movement induces stresses in the crustal rocks (i.e., upper rigid part of a plate), causing them to break along an active fault.

TECTONICS OF STUDY REGION

In the process of continuous subduction of the Indian continental lithosphere, the push from the Asian side has given rise to compression from north, which produces several major thrusts in the region. The Indus Tsangpo Suture (ITS) developed in the first phase at the boundary between the two mega plates and then the MCT, MBT, and MFT respectively developed towards the south (Fig. 2). All of these master thrusts expand all along the study region and also along the entire frontal zone of the Himalayan belt. Some of them also appear in tectonic windows at several places. There is no great variation in the tectonics of the Lesser Himalayan zone. There are several major crystalline thrust sheets and

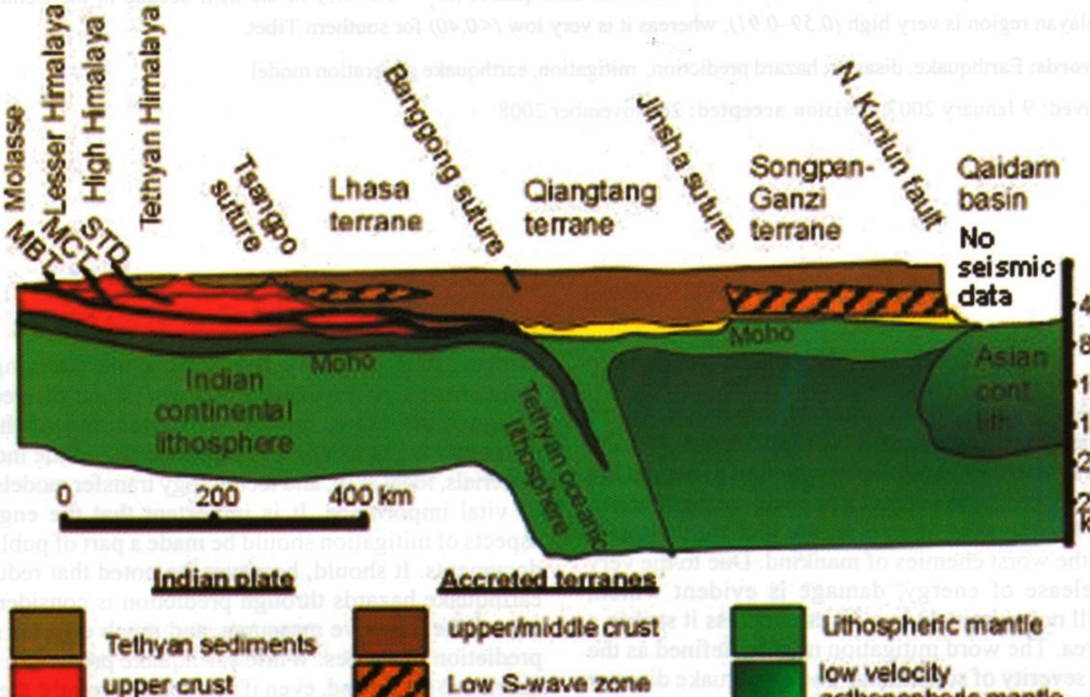

Fig 1. Cross-section through the main units of the Himalaya from the Indian plate in the south (left) to the Asia margin in the north (right) showing the proposed deep underthrusting of Indian lithosphere below Asia at least as far as the northern margin of the Lhasa block (redrawn after Owens and Zandt 1997)

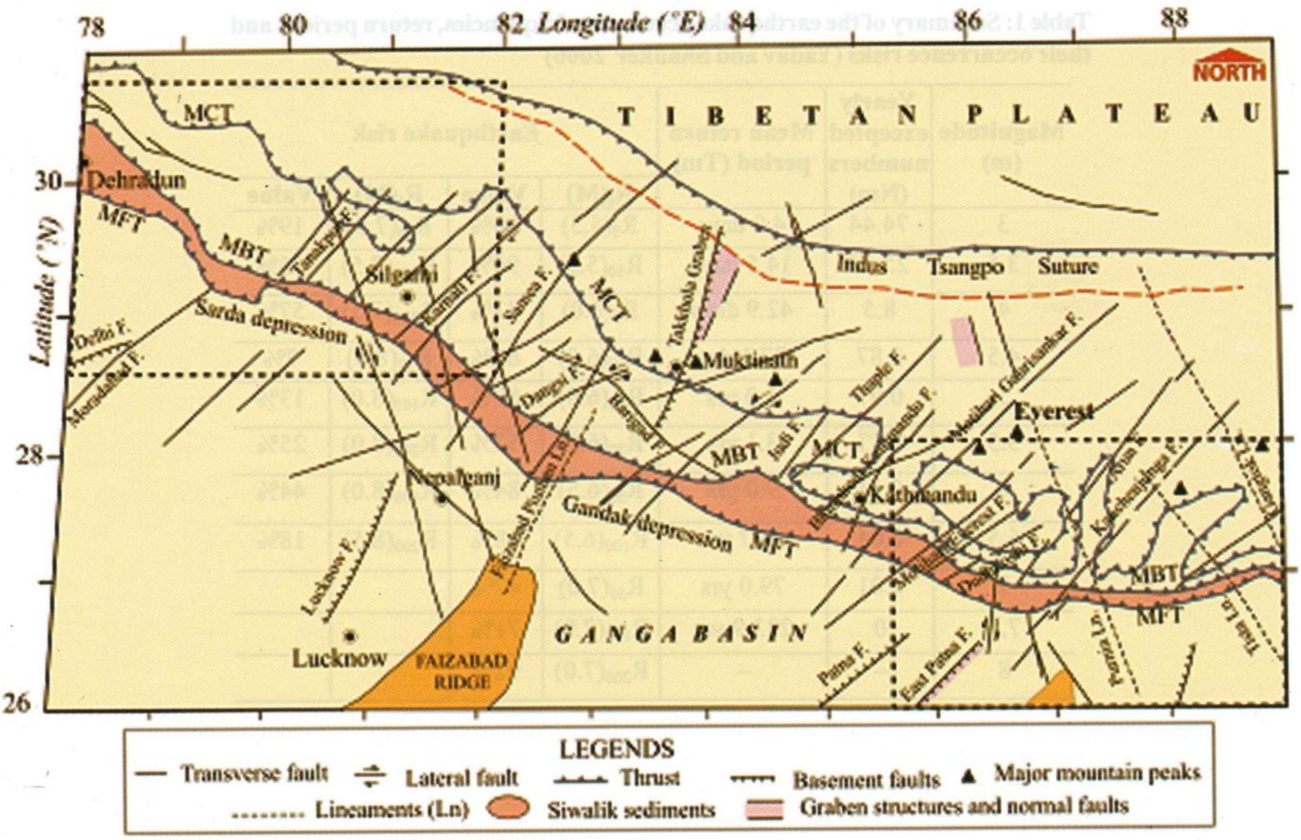

Fig 2. A simplified tectonic map with faults and major lineaments. Some unnamed lineaments, are also shown.

faults in the region, like the Phalebas Thrust in mid-western Nepal, the Bari Gad Fault in western Nepal extending 150 km in NW–SE direction, and others. Among these, the Bari Gad Fault is considered to be an important one in the Lesser Himalaya. In western Nepal, Darma Fault, Bari Gad Fault, and the Thakkhola Fault are important (Jouanne et al. 1999). Late Quarternary faulting in the Lesser and Higher Himalaya extends from the Bari Gad Fault to Darma Fault and is the SE projection of the right-lateral Karakoram fault zone. A number of geoscientists have carried out geological as well as tectonic investigation in the Himalaya and its adjoining areas (Upreti 1999; Hodges 2000; Avouac 2003; Yin 2006). To understand the future earthquake occurrence, time- and magnitude-predictable models have been applied. These models are useful for the assessment of long-term seismic hazard in the region.

Present study includes the Central Himalaya (26°–31° N, 79°–90° E) and Table 1 summarises predicted earthquake occurrence frequencies, return periods, and their occurrence risks in the region based on the extreme value theory.

EARTHQUAKE RECURRENCE MODELS

Most of the earthquake generation models currently used for seismic hazard evaluation are based on the assumption of Poisson or other memoryless distribution, i.e. low-magnitude earthquakes follow the Poisson distribution (random event) and large-magnitude events follow the exponential distribution (non-random). These models are based on the assumption that the time of occurrence and magnitude of an earthquake in a region are independent of time and magnitude of previous or subsequent earthquake in that region. Although the independent behaviour of the earthquake generation has been shown for seismic sequences of same regions. Temporal dependence between earthquakes in several regions has been observed. The time-dependent models can improve considerably our understanding of earthquake generation process and can lead to the accurate evaluation of seismic hazard. It has been observed that active faults or seismogenic sources show regularity in earthquake occurrence. Based on the analyses of coseismic slip on faults, various earthquake prediction models are developed (Fig. 3).

Table 1: Summary of the earthquake occurrence frequencies, return periods and their occurrence risks (Yadav and Shanker 2006)

Magnitude (m)	Yearly excepted numbers (Nm)	Mean return period (Tm)	Earthquake risk			
			$R_t(M)$	Value	$R_t(M)$	Value
3	74.44	4.9 days	$R_5(5.5)$	80%	$R_{50}(7.5)$	19%
3.5	25.15	14.5 days	$R_{10}(5.5)$	96%	$R_{100}(7.5)$	35%
4	8.5	42.9 days	$R_5(6.0)$	42%	$R_{200}(7.5)$	57%
4.5	2.87	127.1 days	$R_{10}(6.0)$	67%	$R_{50}(8.0)$	7%
5	0.97	1.0 yrs	$R_{20}(6.0)$	89%	$R_{100}(8.0)$	13%
5.5	0.33	3.1 yrs	$R_{20}(6.5)$	52%	$R_{200}(8.0)$	25%
6	0.11	9.0 yrs	$R_{50}(6.5)$	84%	$R_{400}(8.0)$	44%
6.5	0.04	26.7 yrs	$R_{100}(6.5)$	98%	$R_{200}(8.5)$	18%
7	0.01	79.0 yrs	$R_{50}(7.0)$	47%		
7.5	0	233.9 yrs	$R_{100}(7.0)$	71%		
8	–	–	$R_{200}(7.0)$	92%		

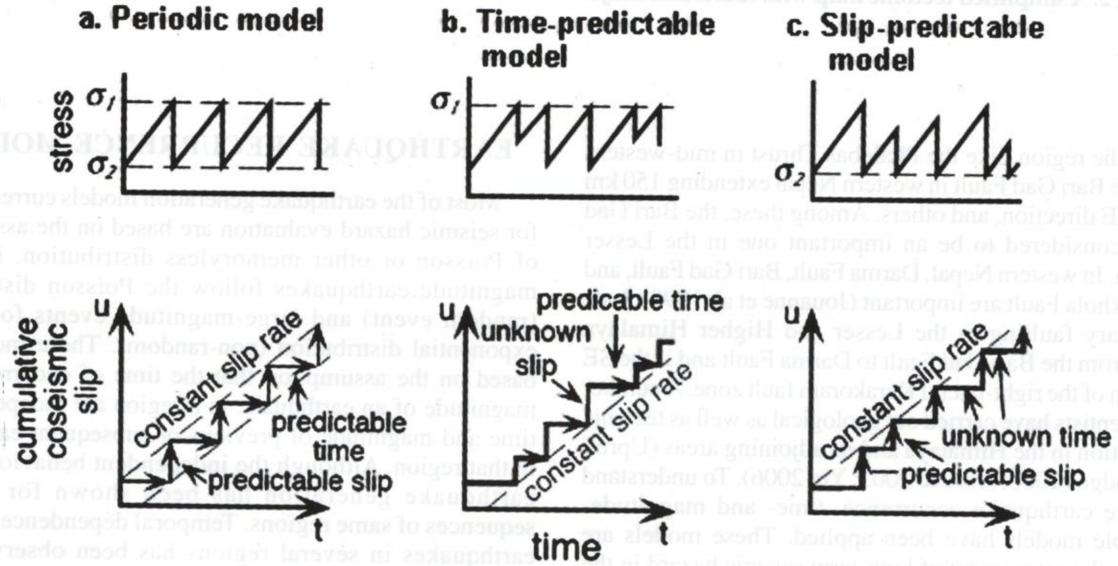

Fig. 3: Schematic illustration of earthquake prediction models.

Methodological requirements

The method includes the following steps:

- Zonation
- Homogeneity and completeness of data
- Seismic moment rate
- Declustering of data
- Time distribution of main shock
- Determination of the parameters

Calculations of probabilities and magnitude of expected main shock

Declustering of data means separating main shocks from foreshocks and aftershocks. The behaviour of the main shocks, that is, the strong earthquake, which remains in the catalogue after removing pre-shocks and post-shocks, can be periodic or quasi-periodic. Kagan and Jackson (1991) defined a coefficient of variation, C_v, of earthquake inter-event time, as a ratio, $C_v = \sigma/T$ (mean), of the standard deviation σ, to the mean repeat time. The coefficient $C_v = 0$ for a periodic behaviour of the shocks and $C_v = 1$ for the Poissonian distribution. For the value of this ratio between $0 < C_v < 1$, the distribution is quasi-periodic and for values of $C_v > 1$, shocks are clustered. In order to check the validity of the model, a grid of equally spaced points at 0.5 degree interval has been created for the Nepal Himalaya and its vicinity, and the main shocks located within each circle with the centre at a point and radius equal to 50 km were first considered. When the number of the main shocks within the circle was four or larger, regression was performed and the *c* value was calculated, otherwise the radius was enlarged by steps of 10 km up to 100 km until this criterion was fulfilled. In 90% of the cases with sufficient data the parameter *c* was found positive, which strongly supports the validity of the model. Based on these criteria six seismogenic sources have been identified to test the model as shown in Fig. 4.

Time-dependent seismicity study in six seismogenic sources of Central Himalaya (Nepal and adjoining areas) reveals that moderate-size shallow earthquakes in each of six sources exhibit intermediate time clustering. The inter-event times between successive shallow main shocks with a magnitude equal to or larger than certain cutoff value were considered for each of these sources and used for each source for long-term earthquake prediction. For the region, the following relations have been derived

$$\log T_t = 0.46M_{min} + 0.07\,M_p + 0.02\log m_0 - 2.38$$

and

$$M_f = 0.78M_{min} - 0.25\,M_p - 0.04\log m_0 + 4.32$$

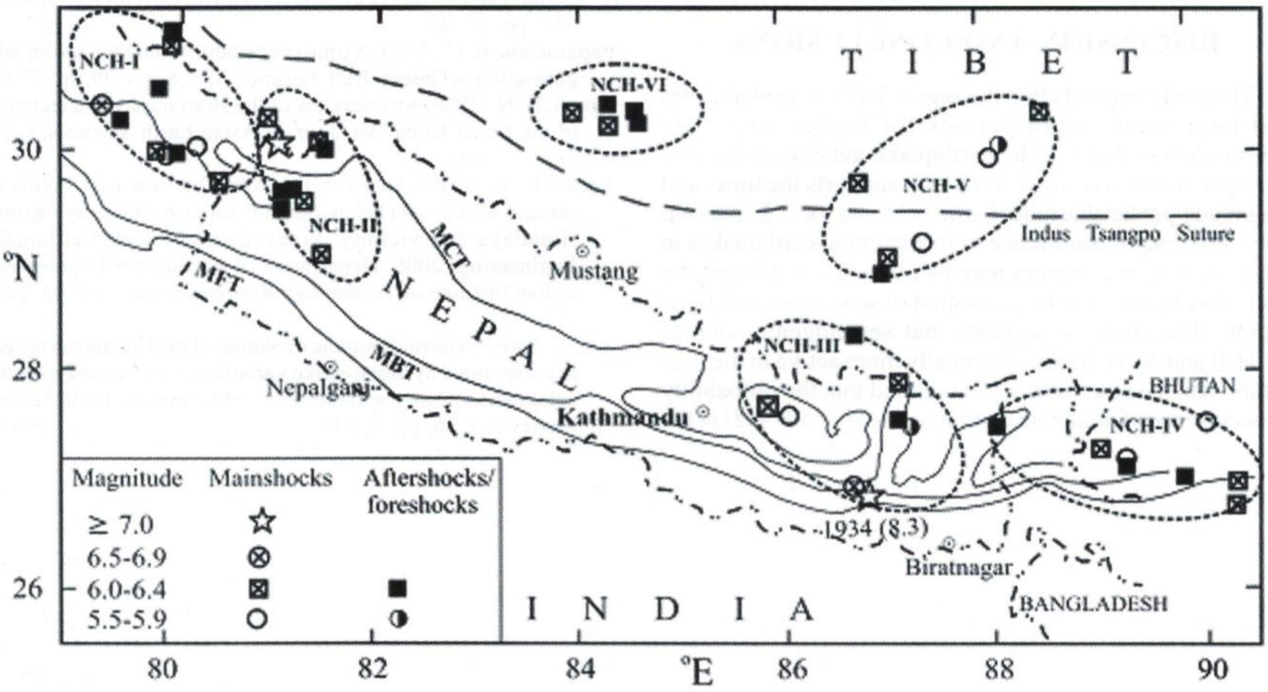

Fig. 4: Six identified seismogenic sources and spatial distribution of main shocks, foreshocks, and aftershocks with $Ms \geq 5.5$ that have occurred in and around Nepal, Central Himalayan region, during the last 90 years from 1916 to 2005. The six seismogenic sources (NCH-I to NCH-VI) delineated based on the clustering of these events are shown by elliptical areas.

Table 2: Magnitude of expected following earthquake M_f and the corresponding conditional probabilities P_{10} from 2005 for the occurrence of large shallow earthquakes with $M_{min} \geq 5.5$ in Nepal and its adjoining regions of Central-Himalaya (Mp - magnitude of the preceding). The zones NCH-II and NCH-III are potentially hazardous in next 10 years.

Seismogenic sources	$M_f \pm 0.2$	P_{10}	M_p
NCH-I	5.8	0.59	6.6
NCH-II	6.4	0.85	6.0
NCH-III	6.0	0.91	6.6
NCH-IV	6.2	0.61	5.5
NCH-V	6.5	0.39	5.5
NCH-VI	6.5	0.04	6.2

where T_t is the inter-event time, measured in years, M_{min} is the moment magnitude of the smallest main shock considered, M_p is the magnitude of preceding main shock, M_f is the magnitude of the following main shock, and m_0 is the moment rate in each source per year. The value of $\sigma = 0.22$ and 0.30 and multi-correlation coefficient, $R=0.62$ and 0.59 for the above two equations, respectively. Based on these relations and using the magnitude and time of occurrence of the last main shocks in each seismogenic source, time-dependent conditional probabilities as well as the magnitude of the expected main shocks ($M_{min} \geq 5.5$) during the next 10, 20, and 30 years are predicted.

DISCUSSION AND CONCLUSIONS

The study suggests that the region has low probabilities and large mean return periods for higher-magnitude earthquakes (Table 1). The earthquake generation process in Nepal– Central Himalayas (NCH) supports the time- and magnitude-predictable model, which is valid for $5.5<Ms<8.6$ only. The time of occurrence of forthcoming earthquakes in these seismogenic sources may be estimated and hence the study may be used for the evaluation of seismic hazard in the region. The analysis suggests that seismogenic sources NCH-II and NCH-III are seismically more active in the near future than the other sources. It is found that the probability of occurrence of moderate earthquakes ($M_s = 5.8–6.5$) in the next decade in the Central Himalayan region is very high (*0.59–0.91*), whereas it is very low (*<0.40*) for southern Tibet (Table 2). Hence, care must be taken while planning future developmental activities in the Central Himalayan region.

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