Probabilities of occurrence of great earthquakes in the Himalaya

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Long-term conditional probabilities of occurrence of great earthquakes along the Himalaya plate boundary seismic zone have been estimated. The chance of occurrence of at least one great earthquake along this seismic zone over a period of 100 years (beginning the year 1999) is estimated to be about 0.89. The 100-year probability of such an earthquake occurring in the Kashmir seismic gap is about 0.27, in the central seismic gap about 0.52 and in the Assam gap about 0.21. The 25-year probabilities of their occurrence in these gaps are 0.07, 0.17, and 0.05 respectively. These probability estimates may be used profitably to assess the seismic hazard in the Himalaya and the adjoining Ganga plains.

1. Introduction

The Himalayas have risen as a result of repeated refracturing of India's advancing limb under persistent compression, and stacking of its sliced front onto itself over a long geologic period that began about 55 million years ago. The occurrence of great earthquakes is inherent in such a process. Although historical evidence is quite incomplete, the region has recorded a number of such earthquakes since 1250 B.C. (Iyengar and Sharma 1998). In the most recent sequence, four great earthquakes have ravaged about half of the Himalayan arc: 1897 in Assam, 1905 in Kangra, 1934 in Bihar-Nepal, and 1950 in Assam, (figure 1) taking a toll of over 30,000 people and causing heavy economic losses. The relative convergence of India and Eurasia, which provides the energy released by these earthquakes, continues unabatedly as evidenced by the persistence of these mighty ranges against the wearing down process of erosion. Similar great earthquakes are therefore expected to occur in the future also. In order to assess the seismic hazard from such earthquakes we estimate the conditional probabilities with which they are likely to occur in various segments of the Himalaya in a given interval of time, in the future. We also estimate the combined probability of the occurrence of one or more such earthquakes in any particular segment for the same interval of future time.

We employ the time-predictable model of earthquakes to obtain these probabilities. The model envisages that strain builds up in a steady manner in a fault zone under a long acting geodynamical process. Once, this is released by an earthquake, the recovery of strain begins preparing the region for the next one to occur. The probability of occurrence of the next strain relieving earthquake on a particular fault segment is proportional to the time elapsed since the last one (Rikitake 1974; Hagiwara 1974). That such a process is operative in the Himalaya has been shown by the analysis of the repeat leveling data on the Saharanpur-Mussorie profile (Gahalaut and Chander 1977a).

2. Rupture process of great earthquakes in the Himalaya

Active tectonics in the Himalaya can be visualized from the distribution of earthquakes occurring there. An arcuate belt of moderate-sized earthquakes occurs close to the surface trace of the Main Central Thrust (MCT). The depths of earthquake foci in this belt, lie at about 15–20 km and their fault plane solutions show thrust faulting along gently dipping planes towards the north (Chandra 1978; Ni and Barazangi 1984; Molnar 1990). The rupture zones of the great

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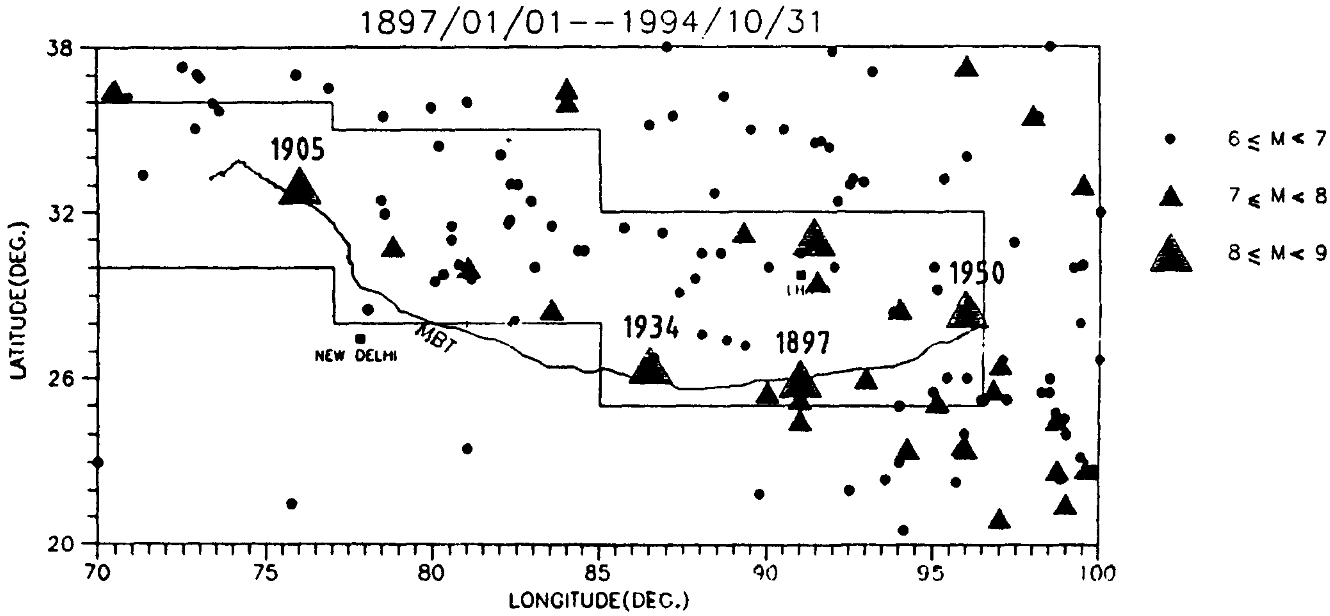

Figure 1. Locations of most recent great earthquakes in the Himalaya.

earthquakes on the other hand, occur on a sub-horizontal fault plane which extends southwards from the zone of the moderate magnitude earthquakes up to the domain of the outer Himalaya (Seeber and Armbruster 1981; Chander 1989; Molnar 1990). This we call the Plate Boundary Thrust (PBT). It dips gently at $\sim 6^\circ$ approximately towards the north and is about 17 km deep at its northern edge, in the region beneath the great Himalaya. The rupture plane has been mapped by reflection surveys by O.N.G.C. in the Doon and the Himachal re-entrants in the foot-hills of the Himalaya (Powers *et al* 1998). Also, deep crustal profiles in southern Tibet have mapped a fault plane called the Main Himalayan Thrust (MHT) which matches the PBT when extrapolated south (Zhao *et al* 1993; Hauck *et al* 1998) into the Himalaya. The above model is consistent with the geological interpretation that major thrusts in the Himalaya dip towards the north, normal to its strike and flatten at depth (Valdiya 1986, 1997). The rupture plane required for modeling of the co-seismic elevation changes during the 1905 great Kangra earthquake is consistent with the PBT model (Chander 1988; Gahalaut and Chander 1992; Gahalaut *et al* 1994). Similarly, the fault plane determined by modeling of the elevation data in Nepal is a similar sub-horizontal plane (Jackson and Bilham 1994; Gahalaut and Chander 1997a and b). The 1934 Bihar-Nepal earthquake has been interpreted to have been caused by slip over PBT which in the N-S direction constrained to lie between the Main Central Thrust and the Main Boundary Thrust in this section of the Himalaya (Chander 1989). Similar inferences have been derived for the 1897 and the 1950 great Assam earthquakes (Chander 1989; Gahalaut and Chander 1992; Khattri 1999).

The episodic slips (displacements during faulting) over sections of this fault cause the occurrence of great earthquakes. The four most recent great earthquakes of $8.1 < M < 8.8$ involved rupturing of sections of the PBT having lengths of about 250–400 km along the strike (Molnar 1990). These rupture zones define intervening sections that have not ruptured for a long time (several hundreds of years) and therefore constitute seismic gaps. Due to the continuing convergence of the plates, the elastic strain which accumulates in these gaps will ultimately be released in the next gap-filling earthquake. The average time cycle of occurrence of great earthquakes in the same section of the plate boundary fault is governed by the strain rate caused by the convergence of the plates. The processes that underlie the great Himalayan earthquakes are of the same nature as those for similar earthquakes of the subduction zones along the Pacific Ocean rim. Hence the earthquake processes in the Himalaya which involve large segments of the PBT are cyclic (Gahalaut and Chander 1977a).

3. Slip rates between the Indian plate and the Himalaya

The estimates of slip rates between the Indian plate and the Himalaya have been obtained on a wide range of time scales. They are consistent among themselves and have therefore been used here for estimating the probabilities of occurrence of future great earthquakes. A long term (time scale of $\sim$one to ten million years) slip rate of 15 ± 5 mm/yr has been obtained from the rate of onlap of Siwalik sediments on to the Indian shield in front of the Garhwal-Kumaon Himalaya (Lyon-Caen and Molnar 1985). Powers *et al* (1998) analyzed balanced cross-sections in the Kangra and Dehradun re-entrants and estimated rates of shortening of 14 ± 2 mm/yr and 6–16 mm/yr respectively in these regions. Using the same technique, the shortening rates of 7 mm/yr (Pennock *et al* 1989) and approximately 13 mm/yr (Leathers 1987; Baker *et al* 1988) are obtained in the eastern and the western Potwar Plateau respectively. Avouac and Tapponnier (1993) estimated a convergence rate of 18mm/yr across the Himalaya. V K Gaur (personal communication) recently determined a convergence rate of 10 ± 5 mm/yr in the Garhwal Himalaya.

The slip rate on the time scale of several thousand years (Holocene) estimated in the Doon valley is > 11.9 ± 3 mm/yr (Wesnousky *et al* 1998) and 21.5± 1.5 mm/yr in the frontal Himalaya of central Nepal (Lave and Avouac 1998).

An analysis of the strain rate distribution in the mobile zone between India and Eurasia has been made using finite element analysis. A strain rate of 18 mm/yr between India and the Himalaya in the Assam and Nepal regions has been obtained. Westwards, the strain rate gradually reduces to 15 mm/yr in the Garhwal Himalaya and to 10 mm/yr in the Jammu Himalaya (Peltzer and Saucier 1996). The slip rate obtained from seismic moments released in great earthquakes during the past one hundred years is estimated to be 17 mm/yr (Molnar 1990; Molnar and Deng 1984). Khattri (1995) obtained a slip rate of 35 mm/yr on primary faults using the fractal model of earthquakes and the complete set of available earthquake catalogs.

Thus on average, the slip rate between the Himalaya and the Indian plate is observed to decrease from a value of about 20 mm in Assam in the east to 10 mm/yr in the west, which is due to the obliqueness of the plate convergence with respect to the Himalaya.

4. Plate boundary fault segmentation: Seismic gaps

The locations of the rupture zones of the four great earthquakes, which have occurred since 1897, are shown in figure 2. On the basis of this most recent cycle of the great earthquake activity, three seismic gaps have been recognized: the Kashmir gap to the west of the Kangra earthquake, the central seismic gap between the Kangra and the Bihar-Nepal earthquakes and the Assam gap between the two Assam earthquakes (Khattri 1999). The extent of the small section of the

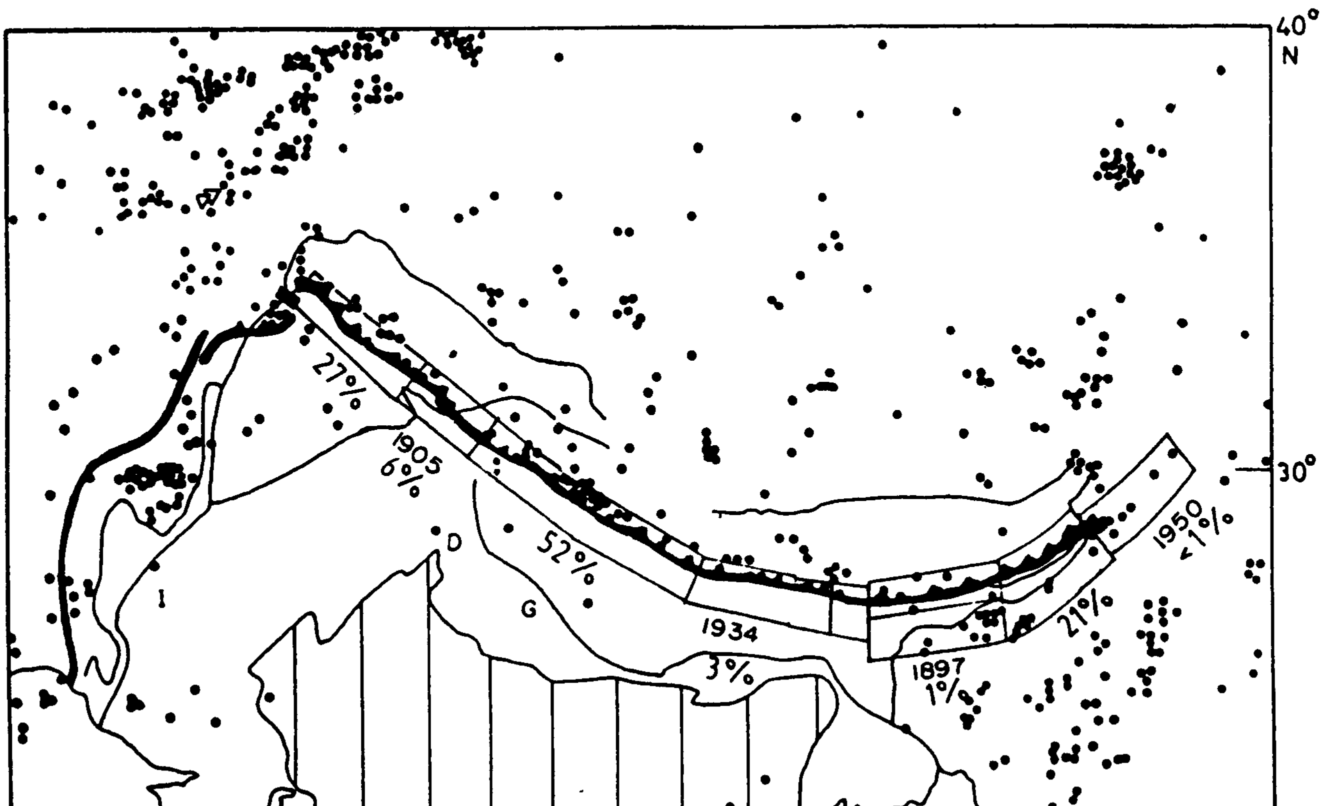

Figure 2. Rectangular strips show the rupture zones and the seismic gaps. The dots show smaller magnitude earthquakes. Conditional probabilities of occurrence of earthquakes of $M \geq 8$ in sections of Himalaya in a time window of 100 years (beginning 1999) are noted next to the strips.

PBT between the rupture zones of the 1934 and the 1897 earthquakes is inadequate to support a great earthquake. Hence it has not been included as a seismic gap in the analysis.

The last great earthquake in the Kashmir gap was the 1555 event for which the maximum intensity has been estimated to be XII (Iyengar and Sharma 1998). Thus this gap has been accumulating strain for the past 450 years.

There is at present no clear-cut information about the last great earthquake in the central seismic gap. The available earthquake catalogs document the occurrence of two large earthquakes in 1803 and 1833 in this seismic gap. However, since the magnitudes of these events were less than 8, they were not in the class of great earthquakes (Oldham 1833; Bilham 1995; Bilham *et al* 1995). The last great earthquake in the Nepal sector of the Himalaya (west of the rupture zone of the 1934-event) was in 1255 that destroyed Kathmandu (Bilham 1995). The time between these two events is 679 years. This interval may serve as a guide for determining a possible time window for the date of the last such event having occurred in the central seismic gap.

The historical records note the occurrences of three large earthquakes in 1548, 1596 and 1696–97 in the Assam gap region (Iyengar and Sharma 1998). The latest of these events is taken as the most recent great earthquake in the Assam gap. A sequence of three earthquakes has also been identified from paleoseismological studies to have occurred around 500, 1100, and 1500 years ago in the rupture zone of the 1897 earthquake (Shillong massif area) (Sukhija *et al* 1996). Therefore the average recurrence interval of great earthquakes in this region may be taken to be about 500 years.

In addition to the above gap, the section of the Himalaya lying to the north of the 1897-rupture may also form a seismic gap. The evaluation of this section is beset with difficulties. The interaction between this section and the southern Shillong massif section and its influence on the strain cycle is not yet clearly understood. Further, no information is available about the previous event there. Thus in the present analysis we have not attempted to estimate the probability for this section separately, the strain cycle having been considered as operative in the entire section as a whole.

5. Procedure of estimating probabilities

The procedure of estimating probabilities of recurrence of great (characteristic) earthquakes is based on the time predictable model of earthquake occurrence (WGOCEP 1990). The strain accumulates continuously which is quasi-cyclically relieved over a fault segment in characteristic earthquakes. There is a positive correlation between the time interval, T, in between successive events on a fault segment and the co-seismic random slip, D, in the previous event. The most probable recurrence time, T^*, to the next earthquake is given by:

$$T^* = (D/V) \tag{1}$$

where D is the best (median) estimate of displacement in the previous segment-rupturing earthquake and V is the best (median) estimate of the long-term slip rate.

The conditional probability of earthquake recurrence is determined from a probability density function of the random time of recurrence, T. The great (characteristic) earthquakes have a relatively narrow range of magnitude and correspondingly narrow range of associated fault slip. Therefore, the associated recurrence time may follow a relatively narrow probability distribution in comparison to the case of Poissonian recurrence model. Other workers have concluded that the results are not sensitive to this choice and have used a log normal distribution (WGOCEP 1990; Nishenko and Buland 1987). The same has been adopted in the present study also. Accordingly probability of occurrence of the next great earthquake in a time window ΔT is given by:

$$P(T_e < T < T_e + \Delta T | T > T_e) = \{P(T_e < T < T_e + \Delta T)\}/\{1 - P(0 < T < T_e)\} \tag{2}$$

where T_e is the elapsed time since the last segment rupturing earthquake, and $P(\cdot)$, the fraction of all earthquake recurrence times in the interval $(t, t + \Delta T)$ is given by:

$$P(t < T < t + \Delta T) = \int_t^{t+\Delta T} \{1/(u\sigma\sqrt{2\Pi})\} \exp\{-[\ln u/T^*]^2/2\sigma^2\} du \tag{3}$$

where T^* is the median recurrence interval of the next segment rupturing earthquake. And σ is a measure of the dispersion in the recurrence time distribution, which includes a parametric uncertainty arising in T^* from the uncertainties in D and V, and an intrinsic variability of event-to-event time when T^* is perfectly known.

6. Probabilities of future great earthquakes

In the calculations we have to specify T_e, the time elapsed up to the present time since the date of the last characteristic earthquake in a fault segment, the time window ΔT, and the value of σ. In the absence of requisite data to empirically estimate the value of σ it's choice has been guided by the experience in California and in the Pacific rim region (WGOCEP 1990; Nishenko and Buland 1987). Two values have been investigated, viz., 0.2 and 0.4. The lower value of σ gives values of the probabilities which are higher by factors of 1.7 (for 100-year) to 2.8 (for 10-year) as compared to the values for

Table 1. *Probabilities of great (characteristic) earthquakes along various sectors of the Himalaya (time windows w.e.f. the year 1999).*

Section	Previous event yr	Probability 10-yr $\sigma = 0.4$	25-yr 0.2	25-yr 0.4	100-yr 0.4
Kashmir gap	1555	0.03		0.07	0.27
Kangra rupture	1905	<0.00		<0.00	0.06
Central gap	1505	0.07	0.42	0.17	0.52
Bihar rupture	1934	<0.00		<0.00	0.03
Assam rupture	1897	<0.00		<0.00	0.01
Assam gap	1697	0.02		0.05	0.21
Assam rupture	1950	<0.00		<0.00	<0.00

the case of $\sigma = 0.4$. A value of 0.4 is considered to be a better choice at the present state of knowledge. Further, experimentation with the date of the last rupturing earthquake as well as the value of T^* shows that the probabilities change only by about ten per cent for a change of about eight per cent in the value of an input parameter. The variations in these parameters are reflected more powerfully in the dispersion parameter. The estimates of the probabilities are shown in table 1 and figure 2. The time windows start from the year 1999.

6.1 *The Kashmir seismic gap*

The last great earthquake in this gap is estimated to have occurred in 1555. The magnitude and the associated fault slip of this event may be taken to be the same as for the 1905 Kangra earthquake, i.e., 8.6 and 6.2 m respectively (Molnar 1990). Then with the constant slip rate of 9 mm/yr for this section the value of T^* will be 555 yr. The 100-year probability in this gap is 0.27. The 25-year and 10-year probabilities are 0.07 and 0.03 respectively.

6.2 *The Central seismic gap*

As discussed in the foregoing the date of the last great earthquake in this gap is uncertain. However we may assume the year of this great earthquake to be 1505 as it coincides with the date of the great destruction of Agra (Iyengar and Sharma 1998), and which could have caused the same. The return period T^* is estimated to be 350 yr using a slip rate of 18 mm/yr and a slip of 6.2 m in the last great earthquake (corresponding to the 1934-Bihar earthquake). Using the above input parameters the 100-yr probability of a great earthquake in this gap is estimated to be 0.52. However since the central gap is long enough to be able to support two great earthquakes of the size of the 1934 earthquake this probability applies to either of them. The 25-year probability is 0.17 while the 10-year value is 0.07.

The effect on the estimates of the probabilities by changing the date of the last earthquake by ±100 years is discussed in the section on Discussion and conclusions.

6.3 *The Assam seismic gap*

The last great event in this gap was in the year 1696–97 (Iyengar and Sharma 1998). The slip in this event is taken to be 9 m, the same as in the 1950 event. With the slip rate of 18 mm/yr the return period T^* turns out to be 500 yr. The probability of the next great earthquake in this gap to occur in the next 100 years is estimated to be 0.21. The 25-year probability is 0.05 and the 10-year probability is 0.02.

The probabilities for 10 and 25-year time windows are small in all sections except in the central gap. However, these will be up to about three times the values shown, i.e., become quite significant, in case the dispersion parameter is indeed about 0.2.

The sections of the plate boundary, which had ruptured in the last cycle, have low probabilities of experiencing a great earthquake even in the next 100 years. The 100-year probabilities for 1897 and the 1905-rupture zones are only 0.01 and 0.06 respectively, while the others have values less than 0.00.

Assuming that the occurrence of individual earthquakes is independent the total 100-year probability of experiencing one or more great earthquakes in the Himalaya is given by:

$$P = 1 - (1 - P_1)(1 - P_2)(1 - P_3) \quad (4)$$

where P_i, $1 = 1, 2, 3 \ldots$ are the individual probabilities of the occurrence of earthquakes in various segments respectively. This probability is 0.89. In this calculation, because of its dimension the central gap is treated as capable of supporting two great earthquakes of the 1934 type.

7. Discussion and conclusions

Lack of knowledge about a clear-cut date for the last great earthquake in the central gap introduces an uncertainty in the estimated probabilities for the gap. The historical records are expected to become less reliable as we go back in time. We may assume that the occurrence of a great earthquake within the last 400 years would be historically recorded. Since there is no evidence for such an event in this period, one has to turn towards the earlier period. The year 1505, when Agra was devastated by an earthquake, was considered as a distinct possibility and has been used for the estimation of probabilities. To examine the sensitivity of the probabilities to variations in this date, we altered the date of the last event by ±100 years, i.e. to 1405 and 1605 respectively. The earlier we fix this date, the higher will be the probabilities and vice-versa. For example, if the last event occurred about 400 years ago (1605) instead of in 1505 the 25-year probability will drop from 0.17 to 0.15 (~12%). Similarly if the last event occurred earlier, say in 1405, the probability will increase only marginally and remain more or less the same, i.e., 0.17. Similarly a variation of ±50 yr (~14%)

in the value of T^* (i.e., due to the corresponding variation in the slip in the last event) causes a corresponding change of ∓ 0.03 ($\sim$17%) in the probability. Hence, for the ranges of variations considered here, the estimates are not overly sensitive. Therefore the estimates represent approximately correct values of the probabilities. The above conclusions apply equally to the remaining sectors as well. Thus the estimated probabilities define, with a measure of confidence, the seismic hazard in the Himalaya and the contiguous Ganga plains due to future great earthquakes.

We note that the 100-year probability for the 1905-rupture zone is 0.06 while for the 1897-rupture zone it is only 0.01, although the time elapsed since the last great event is approximately the same for both the zones. This variation reflects the difference in their fault slips, i.e. magnitudes, in the last great events in the respective zones.

The experiences of the past amply demonstrate the holocaust that great earthquakes can perpetrate. For example, the 1905-Kangra earthquake claimed 19,000 lives. Similarly, the 1934-Bihar-Nepal event devastated a vast expanse of populous habitat. A reoccurrence of the Kangra type earthquake today may kill as many as 150,000 people (Arya 1996). Khattri (1998, 1999) has quantitatively demonstrated that in addition to the extremely severe ground motions occurring in the rupture zones of such earthquakes, quite severe ground motions will be experienced over extensive areas in the Ganga plains. Thus, both in terms of the number of lives that are threatened, as well as the extent of economic losses that will follow, running well into thousands of crores of rupees, we are confronted by a problem of considerable proportions.

The grave seismic risk in the region calls for an urgent and sustained mitigation effort on the national level. The organization of such a program could benefit from the experiences of U.S.A. (California) and Japan. The U.N. initiative under the Decade for Natural Hazard Reduction Programs could also be a source from which to draw valuable information.

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