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Human Losses Expected in Himalayan Earthquakes

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Abstract. Quantitative estimates of potential losses that may be caused by future great earthquakes along the Himalaya suggest that as many as 150,000 people may die, 300,000 may be injured and typically 3,000 settlements will be affected in a single event. Scenario results used here vary and are based on ruptures of 150 km segments of the plate boundary at seven positions, where sufficient elastic energy is believed to be stored for magnitude eight earthquakes. The method of calculating these results was calibrated, using the 17 disastrous Indian earthquakes, which have occurred since 1980. About 50 settlements in the region are considered most at risk because in each more than 2000 fatalities may occur.

Key words: seismic risk, human loss estimates, Himalayan earthquakes.

1. Introduction

It is disconcerting to calculate the numbers of fatalities and injured in future earthquakes because grim pictures result, and because such estimates are subject to many assumptions. Nevertheless, uncertain as these estimates may be, one must attempt to make them, as best one can. The motivation for such studies is to provide a quantitative basis for setting priorities in mitigation efforts and to prepare for a realistic scale of a likely disaster. Although the time of future earthquakes is unknown, there is no doubt that magnitude eight classes earthquakes will happen along the front of the Himalaya. The forces of plate tectonics that caused India to collide with Asia, thrusting up the most magnificent mountain chain on the planet, continue to generate great earthquakes in the collision zone.

2. Method

Scenarios of likely future earthquake ruptures are constructed based on the parameters of historic earthquakes. Since 1900, instrumental data have been available for estimating the location and size of earthquakes. For 11 earlier events since 1500, these parameters have been estimated from descriptions of local damage (Bilham, 2004; Ambraseys and Douglas, 2004). Based on their distribution and their occurrence dates, the amount of potential slip accumulated by the constant plate motions since those earthquakes happened has been estimated (Bilham *et al.*, 2001). The results show that large earthquakes in the Himalaya are overdue, even if we assume that a substantial fraction of the plate motion is absorbed by a-seismic creep. Based on average rupture dimensions of the great historic earthquakes (Table 2 of Bilham *et al.*, 2001), the following parameters were selected for a typical scenario earthquake in this region: rupture length 150 km, rupture width 70 km (corresponding to a magnitude of $M = 8.1$, Wyss, 1979), and hypocentral depth 25 km. The scenario epicenters (Figure 1) were placed at the center of the line connecting historical rupture areas, and at the positions for which Bilham *et al.* (2001) calculated accumulated slip (their Figure 1). These are conservative scenarios because at least one rupture, that in 1505, has been much larger (Bilham, 2004; Ambraseys and Douglas, 2004).

In the method for calculating the losses expected from a given earthquake (Shakhramanjyan *et al.*, 2001), the first step is to calculate the ground acceleration (or intensity of shaking) in the region surrounding the earthquake. In QUAKELOSS, the computer code used, this has been done using standard curves for attenuation of seismic waves as a function of distance from the earthquake, modified by an artificial anisotropy factor (preserving the energy radiated) that enhances the intensity along directions of major

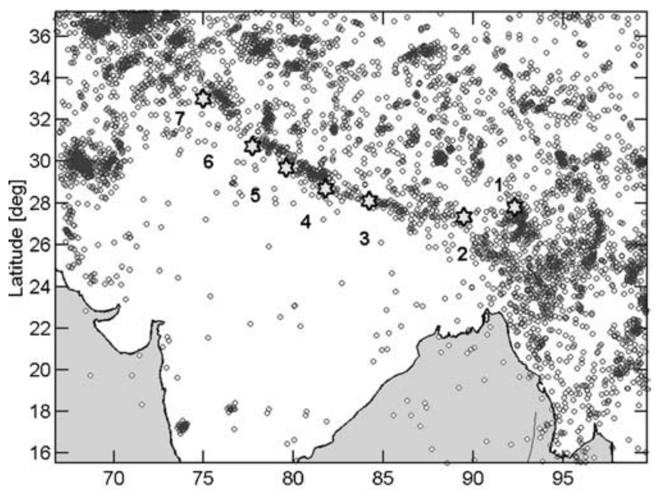

Figure 1. Map showing assumed epicenters of scenario earthquakes (stars), numbered according to Table II. Circles mark shallow epicenters listed by the USGS. Alternative results have been calculated with epicenters in the middle between the stars, because the epicenters of future earthquakes are not known.

faults at the expense of intensities perpendicular to the faults. As second step, follows an estimate of the shaking effect on buildings. The data base of QUAKELOSS contains a distribution (by percentages) of buildings in five classes of fragility in each of about two million settlements worldwide. The fragility is expressed as the probability that a building sustains a given damage level or more, due to the calculated intensity of ground shaking. It is not necessary to know the number of buildings in each settlement, because the population is known. To estimate the impact on humans, one simply needs to know the percentage of buildings sustaining a given level of damage in each of the five fragility classes. Thus, as a third step, the numbers of injured and killed by damaged buildings can be calculated, based on the probability that a given damage state results in a fatality or an injury (Shakhramanjyan *et al.*, 2000). The database of QUAKELOSS contains population numbers for about 20,000 settlements within reach of damaging shaking due to great earthquakes in the Himalaya.

Attenuation laws could vary in the region considered. However, differences in losses, thus introduced, are minor compared to the differences that can result from unknown local site effects. Also, different losses are sustained as a function of the hour of the day, depending on what percentage of people is indoors and outdoors. Although this can be modelled, the hour of future quakes is not known. Here, local time 12 o'clock is assumed because the severity is approximately average at this time.

3. Calibration

Calibration of the results is crucial because engineering surveys of building stock are not available in most parts of the world. For this purpose, a learning database has been used in QUAKELOSS, containing more than 1,000 earthquakes, for which the numbers of fatalities and injured are approximately known (Larionov *et al.*, 2000). The performance of QUAKELOSS in estimating the number of fatalities in Indian earthquakes is evaluated based on all earthquakes listed by the International Disaster Database, back to 1980 (Table I). The estimates agree with the observations within the formal errors (or with a difference of fewer than 10 deaths) in 15 out of 17 cases. In one case, the result is about a factor of two outside the calculated range, which is considered acceptable, and in another case (Latur) it is wrong by a factor of 10. Based on this 88% success rate, and especially its excellent performance in the Bhuj earthquake, by far the most deadly Indian event in the calibration data set, it is reasonable to use this computer code to estimate future losses in India.

In a world-wide performance test of a set of 513 *a-posteriori* and 31 real-time cases of potentially damaging earthquakes, the over-all success rate was 92%, but for the events with more than 1,000 fatalities it was 71% (Wyss,

Table I. Calibration. Numbers of deaths due to earthquakes estimated by the computer program and data base QUAKELOSS, compared to reported numbers for calibrating the method for India. Latitude, longitude, and depth are from the US Geological Survey (USGS) significant earthquakes list, except for some depths derived by moment tensor solutions of Harvard (www.seismology.harvard.edu/CMTsearch.html).

Date	Hour★ (GMT)	Location	Latitude (degree)	Longitude (degree)	Depth (km)	Magnitude (USGS)	Deaths* reported	Deaths estimated	Error (±)
1980/07/29	15	Nepal	29.600	81.090	18	6.5	50	190	80
1980/08/23	22	Kashmir	32.910	75.630	(25)15	(5.2)5.5	13	2	2
1980/11/19	19	Sikkim	27.200	88.390	(17)44	6.1	0	0	0
1981/09/12	7	Kashmir	35.690	73.590	(33)10	5.9(6.2)	212	200	80
1984/12/30	24	Assam	24.400	92.340	(23)10	5.6	20	21	9
1986/04/20	7	Dharmsala	32.128	76.374	33	5.5	6	6	6
1988/02/06	15	Bangladesh	24.688	91.570	15	5.8	2	5	3
1988/08/06	1	Manipur	25.149	95.127	91	7.2	2	3	2
1988/08/20	23	Udaypur	26.755	86.616	35	6.8	721‡	1105	415
1989/06/12	0	Bangladesh	21.861	89.763	6	5.8	1	0	0
1991/10/19	21	Uttarkashi	30.780	78.774	10(25)	7	1500	675	275
1993/09/29	22	Latur	18.066	76.451	7	6.2	9782	1180	720
1997/05/08	23	Bangladesh	24.894	92.950	35	6.0	0	0	0
1997/05/21	23	Jabalpur	23.100	79.590	(36)15	5.8	43	20	14
1999/03/28	19	Chamoli	30.510	79.400	(15)25	6.6	100	152	68
2001/01/26	3	Bhuj	23.419	70.232	(16)20	7.7	20005	18450	6050
2002/09/22	22	Andaman	13.010	93.140	21	6.5	2	2	2

*From International Disaster Database (IDD), ‡from USGS. The error is to be applied as ± to the estimated number of deaths, and represents a formal estimate of two standard deviations, resulting from the probability calculations, but not accounting for errors and unknowns in source parameters, wave transmission properties and building fragility. ★Rounded to the nearest full hour.

2004). This showed that in general the losses in small events are estimated more accurately than in large ones. However, the greatest uncertainty exists for intermediate disasters. Very large events, as those considered here, are reasonably well modelled.

4. Results

The results of seven scenario calculations vary from a minimum in expected fatalities of about 15,000 for an event located in sparsely populated western Nepal, to a maximum of approximately 150,000 deaths for an event located near the Dehra Dun segment (Table II), assuming the standard magnitude of 8.1, and the positions suggested by Bilham *et al.* (2001) (Figure 1). The number of injured is expected to range from 40,000 to 250,000, approximately. Half of the injuries would be slight. The number of affected settlements (about 2,000–4,000 in the different scenarios, Table II, Figure 2) is defined as those expected to experience intensity five or larger on the Modified Mercalli scale, because slight damage can occur at that level. The number of settlements in which some fatalities may occur is roughly measured by those where intensities reach seven or larger (160–550 per scenario, Table II; black and red dots in Figure 2).

The distribution of affected settlements (Figure 2) shows that even in many parts of the Himalaya they are numerous. Although most of these settlements are small, the sum of the population affected in a single scenario is approximately 40 million, on average, if one classifies those people living in

Table II. Estimated human losses due to scenario earthquakes along the Himalayan plate boundary. Latitude, Longitude, depth, and magnitude, M, are assumed, based on parameters of historic earthquakes and the tectonic setting. The range of deaths and injured includes two standard deviations from the mean. The number of settlements expected to experience shaking of intensity, I, larger than 7 and 5, represents those where some people may be killed and those affected by the earthquake, respectively.

	Location.	Latitude (degree)	Longitude (degree)	Depth (km)	M	Expected deaths (thousands)	Number injured (thousands)	No. settle $I \geq 7$	No. settle $I \geq 5$
1	Assam	27.8	92.3	25	8.1	24–49	52–99	160	1900
2	Bhutan	27.3	89.5	25	8.1	76–151	163–274	270	2500
3	Katmandu	28.1	84.2	25	8.1	21–42	45–86	330	2600
4	W. Nepal	28.7	81.8	25	8.1	11–22	24–53	370	2800
5	Garhwal	29.7	79.6	25	8.1	58–115	125–230	380	3000
6	Dehra Dun	30.7	77.7	25	8.1	96–199	210–433	450	3300
7	Kashmir	33.0	75.0	25	8.1	67–137	146–293	550	4000

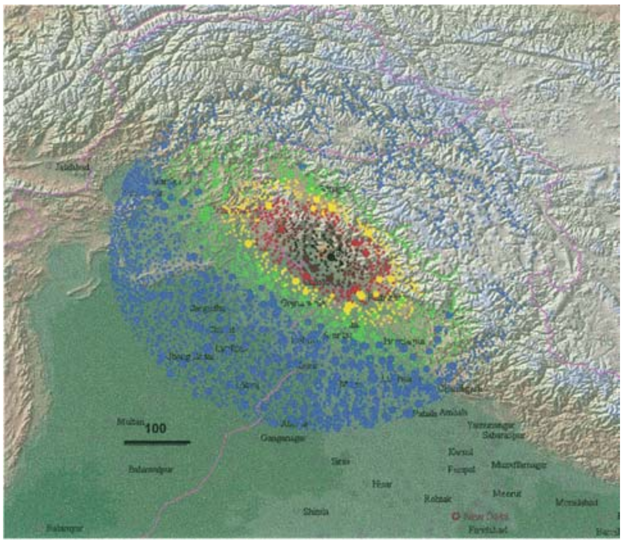

Figure 2. Map of settlements affected by earthquake scenario 7 (Table II). The size of the dots are proportional to the population the settlements, the colour indicates the estimated degree of damage (blue = light, green = moderate, yellow = medium, red = strong, brown = heavy, black = total collapse)

the area of intensity V and larger as affected. Coloured dots in Figure 2 show the estimated degree of damage in one of the scenarios.

The cities with the greatest earthquake risk may be defined as those where more than approximately 2000 deaths are expected in any of the scenarios. There are 47 of them in the region (Table III). Mitigation measures may be most effective in these cities. These quantitative estimates of potential human losses in great earthquakes along the Himalaya show that the combination of great earthquakes and the large population numbers is likely to produce major disasters. Thus, response, preparedness and mitigation plans should be made on a major scale.

5. Discussion

The assumptions and approximations that enter the loss estimates are numerous and many sources of error exist. First, the parameters of the earthquakes that will happen (magnitude, location and depth) will be different than those assumed in the scenario prototypes. However, the larger the earthquake, the less the details influence the overall outcome because the probability calculations are more likely to be fulfilled. For small earthquakes, the results can depend critically on the depth and exact location, because

Table III. Cities where one of the scenario earthquakes in the Himalaya may cause 2,000 or more fatalities, ordered by severity of the disaster. These are not predictions, and it is not known which cities will be affected in the next great Himalayan earthquake. It is simply a list of settlements where the combination of proximity to a potential earthquake and its size make them vulnerable. Cities in countries other than India are identified (Bhu = Bhutan, Chi = China, Nep = Nepal)

1	Udhampur	17	Taga(Bhu)	33	Churang(Bhu)
2	Almora★	18	Yatung(Chi)	34	Yatung
3	Ranikhet★	19	Musurie	35	Samba
4	Getta-Dzong(Bhu)	20	Duka-Jong(Bhu)	36	Champavat★
5	T-himbu(Bhu)	21	Simla	37	Jutogh
6	Ha-Jong(Bhu)	22	Paontasahib	38	Rajpur
7	Dehra-Dun	23	Rampura	39	Kathmandu(Nep)×
8	Jammu	24	Landour	40	Kota-Bag★
9	Gurkha(Nep)×	25	Akhnur	41	Trashiyagsi-Dzong(Bhu)
10	Sahaspur	26	Chandigarh	42	Lansdovne★
11	Chakrata	27	Punakha(Bhu)	43	Ramnagar★
12	Chaubattiya★	28	Solon	44	Kalka
13	Cona(Chi)	29	Nainital★	45	Gang-T-ok
14	Chuharpur	30	Twang-Shyo	46	Pathankot
15	Some-Jong(Bhu)	31	Nahan	47	Hrdvar
16	Vangdupotrang(Bhu)	32	Tithoragarh★		

★Mark settlements affected by scenario 5, ×those by scenario 3. The Table contains no settlements associated with scenario 4.

their small footprint may or may not include the single largest town in the area, which is the single largest potential contributor of fatalities. The influence on results by shifting epicenters assumed in the scenarios was estimated by repeating the loss calculations, using epicenters also located in the seismic gaps (Bilham *et al.*, 2001), but half way between those shown as stars in Figure 1. The results approximated the numbers one would expect by interpolating values of neighboring scenarios in Table II, but were lower, on average, by 30%. This logic of shifting the epicenters for alternative estimates emphasizes that no predictions of specific earthquakes are made here. It is not known when and where future events will occur and how large they will be, exactly.

Misjudgment of the regional building fragility could be a significant source of error. The calibration events (Table I) were not all from the Himalayan region and not from all the culturally dissimilar areas. The underestimate of the fatalities in the Latur earthquake (Table I) is probably in part due to the exceptionally thick and heavy mud roofs placed on poorly constructed walls in the town of Killari; a construction style not adequately reflected in the data base. Also, the Latur earthquake radiated more energy than normal in high frequency bands, not toppling the town's water tank (a notoriously precarious distribution of weight), but collapsing the single story houses in Killari. Factors which lead to such exceptional effects as in the Latur earthquake also include unusual soil conditions. Many cases are known where parts of cities are built on layers of unconsolidated soil, where resonance of the arriving seismic waves with buildings of a certain height leads to excessive damage, as in Mexico City during the 1985 Oaxaca earthquake at a distance of more than 300 km. Such conditions might be present in the Ganga plain and have not been taken into consideration by the computations reported here. These effects could be accounted for in the calculations, if the conditions were known.

Effects that can cause significant devastation, but are not included in the estimates here are landslides, flooding due to breaking dams, fires and spilling of hazardous materials from industrial facilities. In spite of the reservations discussed above, it is reasonable to propose that the calibration (Table I) indicates that the transmission of seismic energy, fragility of the building stock and other parameters are adequately estimated, on average.

Estimating the potential present day losses of repeats of historic earthquakes might be used to gauge the development of the seismic risk in the Himalaya and adjacent regions. The increase in the risk today, compared to decades and a century ago ranges from a factor of 3 to 60, varying regionally (Table IV). The two major factors for the worsening of the risk are increases in population and building fragility. The growth of the population is a tractable parameter, but the increase in fragility of buildings is difficult to ascertain, although it may be significant. For example, where poorly constructed masonry buildings replace wooden and bamboo-structures, the danger for the inhabitants is dramatically increased (B. Tucker, pers. comm. 2003).

The accuracy of the human losses estimated here should not be overestimated, and alternative approaches should be used to check their reliability.

Table IV. Estimates of current disasters if repeats of historic earthquakes should happen. Expected deaths are calculated by QUAKELOSS, the reported numbers are from the IDD.

Date	Time (GMT)	Location	Latitude (degree)	Longitude (degree)	Depth (km)	M	Expected deaths	Reported deaths
1897/06/12	11:06	Shillong	26.0	91.0	20	8.3	90,000	1,542
1905/04/05	00:50	Kangra	32.1	76.4	25	8.0	70,000	20,000
1934/01/15	08:43	Bihar	27.55	87.09	30	8.1	18,000	6,000 (10,500)*
1950/08/15	14:09	Assam	28.5	96.5	30	8.6	40,000	1,500

*From [2].

For example, the accelerations expected by the GSHAP project (Bhatia *et al.*, 1999) (www.seismo.ethz.ch/GSHAP/eastasia/), or those calculated for specific models of great ruptures (Khattri, 1999) could be used alternatively to estimate the losses in the settlements in the QUAKELOSS database. Given the relevance to human losses of the estimates presented here, all possible improvements in the method to estimate them should be implemented.

6. Conclusions

The seismic risk due to Himalayan earthquakes has increased by an order of magnitude over the last century, as the quantitative comparison of losses observed in historic and those expected in repeat earthquakes shows (Table IV). However, the scenario earthquakes and their associated disasters (Table II) are more likely to occur than repeat events. The probability that at least one great earthquake will occur in the Himalaya during the next 98 years has been estimated as 0.89 (Khattri, 1999), and the probability for each of the scenarios 3 through 6 (Table II) has been estimated as 0.52 (Khattri, pers. comm., 2003), which is higher than for the other scenarios. Given these estimates and the position of the 1803 rupture shown by Bilham (2004, his Figure 4; Ambraseys and Douglas, 2004), the scenarios 3–5 seem to have the greatest probability to occur. Therefore, it may be a good strategy to give high priority to mitigation efforts in those 10 cities in Table III, which are expected to be affected by these scenarios.

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