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LETTER
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Fatality rates of the M_w ~8.2, 1934, Bihar–Nepal earthquake and comparison with the April 2015 Gorkha earthquake

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Abstract

Large Himalayan earthquakes expose rapidly growing populations of millions of people to high levels of seismic hazards, in particular in northeast India and Nepal. Calibrating vulnerability models specific to this region of the world is therefore crucial to the development of reliable mitigation measures. Here, we reevaluate the >15,700 casualties (8500 in Nepal and 7200 in India) from the M_w ~8.2, 1934, Bihar–Nepal earthquake and calculate the fatality rates for this earthquake using an estimation of the population derived from two census held in 1921 and 1942. Values reach 0.7–1 % in the epicentral region, located in eastern Nepal, and 2–5 % in the urban areas of the Kathmandu valley. Assuming a constant vulnerability, we obtain, if the same earthquake would have repeated in 2011, fatalities of 33,000 in Nepal and 50,000 in India. Fast-growing population in India indeed must unavoidably lead to increased levels of casualty compared with Nepal, where the population growth is smaller. Aside from that probably robust fact, extrapolations have to be taken with great caution. Among other effects, building and life vulnerability could depend on population concentration and evolution of construction methods. Indeed, fatalities of the April 25, 2015, M_w 7.8 Gorkha earthquake indicated on average a reduction in building vulnerability in urban areas, while rural areas remained highly vulnerable. While effective scaling laws, function of the building stock, seem to describe these differences adequately, vulnerability in the case of an M_w >8.2 earthquake remains largely unknown. Further research should be carried out urgently so that better prevention strategies can be implemented and building codes reevaluated on, adequately combining detailed ancient and modern data.

Keywords: Earthquake, Nepal, Mortality, Fatalities, Power law, Building vulnerability, Mitigation measures

Background

In a context of fast-growing population, more and more people are exposed to large devastating earthquakes (Bilham 2004; Jackson 2006). This is particularly true at the foot of the Himalayan range where such events are given to happen in the coming decades when, on the meantime, the population is expected to grow quickly and aggregate in supercities (Bilham 2009). Indeed, since the last major Himalayan earthquake, the giant M_w ~8.6 August the 15th 1950 earthquake in Assam, the population of the whole Indian subcontinent more than tripled and concentrated in densely populated large cities having yearly growth rates in excess of 20 % (The Registrar General and Census Commissioner, India: censusindia.gov.in). With the recent occurrence of the deadly M_w 7.8 Gorkha earthquake of April 25, 2015 (Adhikari et al. 2015), the estimation of damage and loss of life from future large earthquake becomes an even more pressing priority.

Among the fastest growing in the last decades and actually most dense areas are the Himalayan range foreland basins. These regions were particularly impacted by the 1897 Shillong (Oldham 1899), 1905 Kangra (Middlemiss 1910) and 1934 Bihar (Rana 1935; Dunn et al. 1939) and will be impacted by future earthquakes that will rupture inevitably the Main Himalayan Thrust along the foothills of the mountain range (Fig. 1), with a major seismic gap located between Dehli and Patna and focusing much of the current attention and debates (e.g., Rajendran et al. 2015; Pulla 2015).

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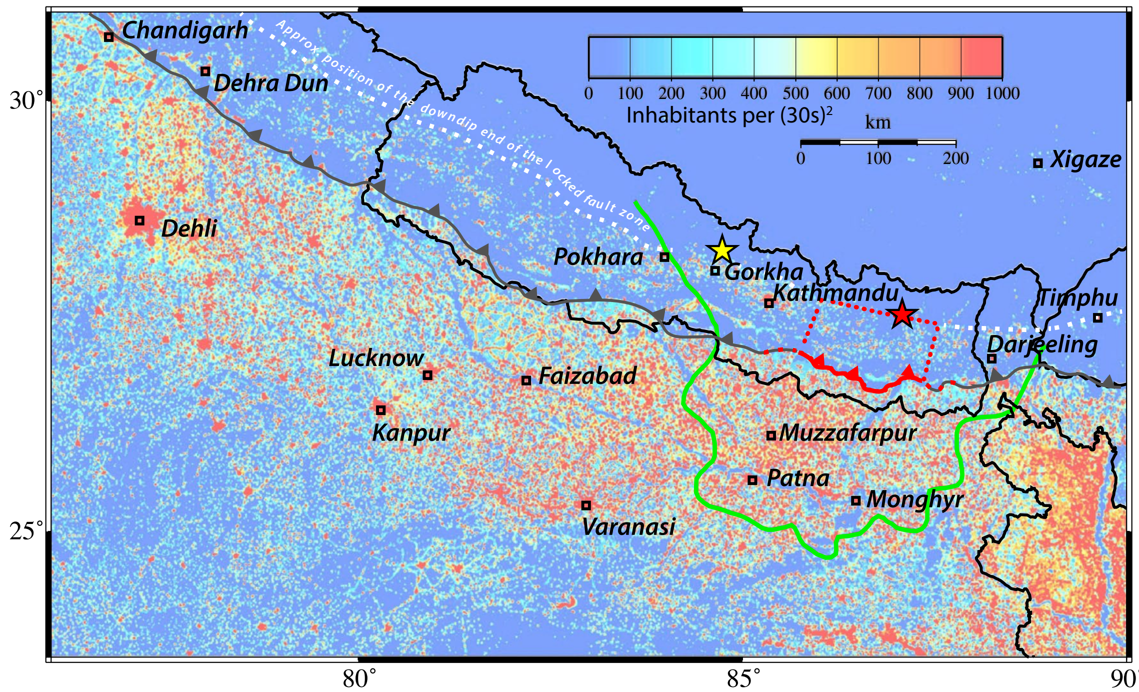

Fig. 1 The great Bihar–Nepal January 15, 1934, earthquake epicenter, *red star* (Chen and Molnar 1977), and the Gorkha April 25, 2016, epicenter, *yellow star*, in light of the present-day population density. The past and future great earthquakes ruptures correspond to the area in between the *thick gray line with triangles* corresponding to the Main Frontal Thrust and the *white dotted line* materializing approximately the position of the downdip end of the presently locked fault zone. The area delimited by the *green polyline* corresponds to the area affected by damages during the 1934 earthquakes (Isoseist VI MSK64 from this study). *Red thick line with triangles* corresponds to the minimum extension of the 1934 earthquake surface rupture (Sapkota et al. 2013) and *red dotted line* to minimum extension of the rupture at depth. The background image is a color-coded 2011 Landscan estimation of the population density

Among the past Himalayan earthquakes, the Bihar–Nepal, January 15, 1934, earthquake, with a death toll of more than 8000 people in Nepal and 7000 in India, deeply traumatized the population. In Nepal, several original testimonies were collected by Brahma Shumsher Rana, a Nepalese army "major general" responsible for the rescue and reconstruction operations (see Additional file 1). Some of these testimonies as well as key scientific information are compiled in his 1936 book, "Mahabukhampa"—"Great Earthquake" in nepali (Rana 1935). It has been partially complemented by the observations made during the three trips organized through the meizoseismal zone in eastern Nepal and Ganges basin (Dunn et al. 1939). A systematic macroseismic data collection was concomitantly organized in India. Indeed, the collection of questionnaires prepared by the Geological Survey of India and sent through the government of Bihar and Orissa were a major source of information in terms of macroseismic effects (e.g., Dunn et al. 1939). These macroseismic surveys resulted in a vast accumulation of data, including death toll and damages, consigned in Rana (1935) and Dunn et al. (1939), compiled and further analyzed in review studies (Pandey and Molnar 1988). However, information on the fatality rates was lacking due to limited availability of any individual and housing census at the time of the event. This lack limited exploitation of the data collected in terms of hazard estimation.

In this article, we determine the casualty rate and its spatial variations in Nepal. For that purpose, we confront the fatality counts with estimates of the Nepalese population repartition deduced from two National populations and housing census carried out in 1924 and 1942. We then extrapolate these fatalities to modern conditions. The difficulties of such extrapolations are illustrated by comparing the 1934 fatality rates with the fatality rates of the April 25, 2015, M_w 7.8 Gorkha earthquake and also scaling laws proposed by Shiono (1995) for the Asian region.

Macroseismic dataset: from collection to interpretation

"It was exactly twenty-four minutes and twenty-two seconds after two PM Nepal time" on January the 15th 1934 (Magh 2 1990 in the Bikram Sambat calendar) "when a strange noise, assimilated to a rumble coming from the earth's interior," was perceived by the Kathmandu valley inhabitants. "This noise was followed by observations of water in reservoirs, basins and containers overflowing and spilling out. Observers then felt the ground moving from east to west before describing it as bended. The strong shaking followed immediately and its arrival induced development of cracks and the collapse of the first houses." These observations described by Bhrama Shumsher Rana in 1935 (see Additional file 1 for his biography and the context of his study) are not limited to Kathmandu valley. Indeed, the author reported widespread damages from Kathmandu to the eastern Nepal border with India. The devastation affected also particularly northern India, and above all a large part of the state of Bihar. The strong damages reported were accompanied by a large number of casualties including a death toll greater than 15,000 people. Comprehensive macroseismic studies carried out in India (Dunn et al. 1939) had suggested at first that the epicenter was located in the Indian plains. Indeed, a 300-km-long region of Bihar, named the "slump belt," was very strongly impacted, in soft ground area, by liquefactions and slumping as well as the place of a metrical subsidence measured by spirit leveling shortly after the earthquake [references and discussions in Bilham et al. (1998)].

B.S. Rana, from the beginning of his book (Rana 1935), refutes this thesis and gives the elements that make him think that the earthquake did happen in Nepal. Among others, he could actually see that many villages were destroyed east of Kathmandu, the damaged area far exceeding the state of Bihar and the Kathmandu valley. He also notes that many landslides were triggered in the east, in the vicinity of Udaypur Gadhi and Dharan (86–87.5°E). He further described the situation in the eastern mountains further north, near the village of Bhojpur (87° E), with the Sanskrit term "patala," somewhat ambiguous in this context, but suggesting the idea of hell (Pandey and Molnar 1988). Concurrently to the first scenario, associating the epicentral region with the state of Bihar, the distribution of heavy destructions along the Nepal foothills as well as further north in the Lesser Himalaya of eastern Nepal rather suggested an epicenter on a fault further north between the front of the high Himalayan range and the Main Frontal Thrust (Rana 1935; Pandey and Molnar 1988).

This second scenario was first consolidated by the instrumental relocation of the epicenter 10 km south of Mount Everest (Chen and Molnar 1977) (Fig. 1). It was then definitely confirmed by the discovery of the traces of a 150-km-long surface rupture along the Main Frontal Thrust in eastern Nepal (Sapkota et al. 2013; Bollinger et al. 2014) (Fig. 1). In the meantime, Hough and Bilham (2008) proposed that the strong intensities in the Gangetic plains, in addition to local liquefaction and site effects, are mostly due to post-critical Moho reflection that led to the focus of an aggressive SmS seismic phase.

In addition to providing qualitative information on the earthquake rupture, the macroseismic data material collected in India and Nepal in 1934 is an invaluable source of quantified observations. The macroseismic questionnaire prepared by the Geological Survey in India has been adapted two times in 1934 to be able to collect the most comprehensive information possible (Dunn et al. 1939). Government reports, newspapers and other materials complemented this information. Besides its qualitative descriptions from Nepal, Rana (1935) also provided a detailed accounting of casualties and damage by location. These data were analyzed by Pandey and Molnar (1988) and seem accurate enough to be considered/investigated with some attention (see Table 1). Note, however, that the casualty counts in Nepal must be taken cautiously, given the number of remote villages that were hit by the earthquake and for which it is doubtful that reliable figures will ever be available. The document also provides statistics on the buildings completely destroyed, heavily cracked and slightly cracked (see Table 1).

Notwithstanding the great quality of this information, the spatial analysis of macroseismic observations is delicate. Indeed, these observations depict a significant local variability partially simulated by biases coming from the observer, the various source of macroseismic information as well as from natural variations inherent to the local geological conditions. These observations were further translated into various intensity scales including MMI (Dunn et al. 1939), MSK-64 (Ambraseys and Douglas 2004) and EMS-98 (Martin and Szeliga 2010) using some subjective choices. Except first-order differences coming from integration (Dunn et al. 1939) or depletion (Ambraseys and Douglas 2004; Martin and Szeliga 2010) of the effects of liquefactions of the soils on buildings, the differences between the interpretations are difficult to clarify [see Szeliga et al. 2010 for quantifications of differences between Ambraseys and Douglas (2004) and Martin and Szeliga (2010)]. Finally, the density of the macroseismic intensities being highly variable along strike the felt area, we tested several interpolation/kriging schemes in order to finally compare fatalities counts and intensities and avoid subjectivity.

Whatever the method used on the intensity dataset depleted from the observations at sites encompassing soil liquefactions, the surface covered by intensities greater than VIII, usually correlated along shallow dipping thrust with the fault segment that ruptured, is relatively stable on the order of 10,800 ± 1600 km^2. It corresponds approximately to the trace of the 150-km-long surface rupture mapped in the field (Sapkota et al. 2013) (Fig. 2). In turn, the typical value kriged within a radius

Table 1 Fatalities count per district due to the January 15, 1934, earthquake (Rana 1935) and comparison with population estimates

	Collapsed building/cracked/damages = total	Fatalities count	Population in 1921 (BS1977)	Population in 1942 (BS1998)	Population estimated in 1934 (BS1990)	Fatality rate (%)
Kathmandu valley						
Kathmandu	725/3735/4146 = 8606	479			81,400	0.59 0.48
Kathmandu vicinity	2892/4062/4267 = 11,221	245			68,600	0.36
Patan	1000/4170/3860 = 9030	547			31,000	1.8 2.2
Patan vicinity	3977/9442/1598 = 15,017	1697			69,000	2.5
Bhaktapur	2359/2263/1425 = 6047	1172			25,000	4.7 2
Bhaktapur vicinity	1444/1986/2388 = 5818	156			40,000	0.39
Total	12,397/25,658/17,684 = 55,739	4296	306,909	323,336	315,000	1.4
Eastern mountain districts						
East district 1 (Chautara)	9628/19,391/– = 29,019	356	213,703	248,787	230,000	0.16
East district 2 (Ramechhap)	4687/10,738/– = 15,425	95	177,072	159,775	170,000	0.06
East district 3 (Okhaldhunga)	21,107/15,548/– = 36,655	857	377,774	388,770	144,000	0.23
East district 4 (Bhojpur)	15,048/5/– = 15,053	1597			236,000	0.68
Dhankuta district	6623/15,120/– = 21,743	316	353,062	381,965	370,000	0.09
Ilam district	2316/3112/– = 5428	92	87,475	91,362	90,000	0.1
Udayapur Gadhi district	1052/3917/– = 4969	552	48,913	39,483	44,000	1.1
Sindhuli Gadhi district	3486/3154/– = 6640	109				
Total	63,947/70,985 = 134,932	3974	1,257,999	1,310,142	1,300,000	0.31
Western mountain districts						
West district 1 (Nuwakot)	582/1720/– = 2302	10	165,251	239,128	200,000	<0.01
West district 2 (Gorkha)	186/461/– = 647	1	72,203	97,386	85,000	<0.01
West district 3 (Pokhara)	19/65/– = 84	1	221,725	274,779	250,000	<0.01
West district 4	8/1/– = 9	1	183,417	256,941	220,000	<0.01
Chisapani Gadhi district	–/18/1266 = 1284	52	66,072	49,659	60,000	<0.01
Total	795/2268/1266 = 4329	65	708,668	917,883	800,000	0.01
Eastern Terai						
Birgunj district	3654/854/2546 = 7054	44	414,557	451,670	430,000	0.01
Mahottari and Sarlahi districts	–/4323/268 = 4591	51	471,292	460,943	470,000	0.01
Saptari and Siraha districts	87/428/– = 515	40	377,855	363,941	370,000	0.01
Biratnagar district	13/1/64 = 78	49	211,308	241,474	230,000	0.02
Jhapa district	–/–/– = –					
Total	3754/5610/2884 = 12,248	184	1,475 112	1,518 028	1,500 000	0.01
Total Nepal	80,893/104,521/21,834	8519	5,537,785	6,283,715	5,900,000	0.15
Total Bihar (Inde)	=207,248	7188			≈15 000 000	

The population estimation in 1921 and 1942 comes from the Central Bureau of Statistics, Katmandu. The population estimation for 1934 is deduced from an extrapolation in between the values for 1921 and 1942. The population distribution in the valley in 1934 is estimated from the 1953 census (BS2009)

of 150–250 km of the epicenter is intensity VII, while intensity VI is reached within 200–300 km. This intensity decrease as a function of the epicentral distance is typical of the decrease predicted by the intensity attenuation laws calibrated with all Himalayan earthquakes (Ambraseys and Douglas 2004; Szeliga et al. 2010).

In order to avoid biases induced (1) by the variable quality of the sparse macroseismic data available in Nepal and (2) by the spatially unresolved accounting of the observations within a district associated with (3) an unresolved high variability of the geological and topographical site effects, we will further compare the destructions and fatalities to "estimated MSK intensities" deduced from Ambraseys and Douglas (2004) and associated with each district centroid. While more recent relations in EMS-98 intensities are presented in the literature for Himalayan

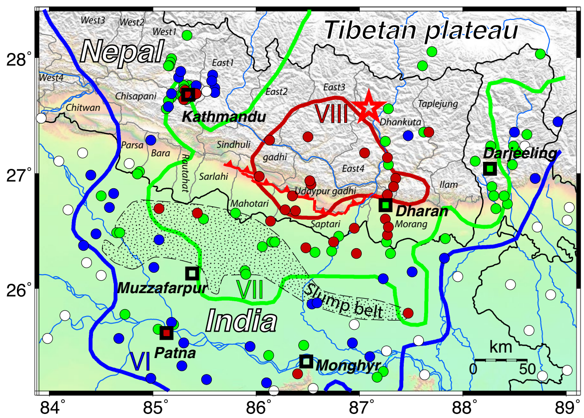

Fig. 2 Macroseismic map of the 1934 earthquake. Isoseists interpolated from 806 MSK64 macroseismic intensities compiled in Ambraseys and Douglas (2004). Slump belt was severely affected by liquefactions and slumping (contour from Dunn et al. 1939). *Red star* is the instrumental epicenter of the main shock from Chen and Molnar (1977). *Red polyline with triangles* corresponds to the trace of the Main Frontal Thrust that ruptured in 1934 according to Sapkota et al. (2013). In *gray*, 1934 administrative districts borders and names. Refer to Table 1 for full district names

earthquakes (Szeliga et al. 2010), we retain this relationship in MSK-64 because it facilitates direct comparison of our results with those of Shiono (1995).

Besides, the distribution of the collapsed buildings and fatalities are far from being as clearly related to the epicentral distance. Indeed, in the eastern districts to the south of the epicenter there are a considerable number of collapsed buildings (see Table 2), suggesting a strong effect of the earthquake despite a comparatively small number of victims. The effects diminish quickly eastward, with little damage to Darjeeling (Fig. 2). To the west, in the Kathmandu valley, the rate of victims per collapsed buildings appears higher than elsewhere suggesting a higher vulnerability of the population to the destructions, most probably due to the taller buildings and higher buildings density (multi-story masonry with mud cement) as well as local site conditions. These observations could therefore benefit from being confronted to demographical records.

Fatality rate collection and analysis

Besides this information on the macroseismic field, we benefited from the individual and housing counts of the Nepalese population issued before (1921) and after the earthquake (1942) by the Central Bureau of Statistics, critical information that was not available to previous studies including Pandey and Molnar (1988). We estimated the population counts in 1934 from an extrapolation in between the values for these censuses, estimating the average annual growth rate for each region and making the hypothesis that these rates are constant over the considered period. Given that we did not benefit from details concerning the population repartition within the Kathmandu valley in 1921 and 1942, we used those from the 1953 census, making the hypothesis that the distribution of the population remained similar up to at least 1953 (Table 1). The growth rate remained smaller than 1 % per year during that period; therefore, uncertainties, conservatively taken as 5 % when necessary, have no consequence on the conclusions we reach in this study.

We then confront, to evaluate the fatality rate, the number of victims reported by Rana (1935) to this estimate of the 1934 population. These numbers are summarized in Tables 1 and 2. In Kathmandu valley, the fatality rate appears higher than in other areas of the meizoseismal zone in Nepal (Fig. 2). Indeed, the fatality rates in Kathmandu, Bhaktapur and Lalitpur–Patan districts are typically as high as 0.5 % or larger, while they rarely reach 0.1 % in most regions at similar distances from the epicenter. Actually, the fatality rate is of the order of 2 % for Patan, similar in and out the city center due to a mixed type of building, but varies in between 0.4 % for the most rural areas in Bhaktapur

Table 2 Fatality rate due to the January 15, 1934, earthquake in the Kathmandu valley

Area	Surface (km^2)	Fatality rate in 1934 (%)	Population estimated in 1934	Population density in 1934 (per km^2)	Population in 2011	Population density in 2011 (per km^2)
Kathmandu city	49.45	0.59	81,400	1646	1,003,285	20,290
Kathmandu vicinity	345	0.36	68,600	199	696,004	2017
Kathmandu district	395		150,000		1,699,289	4302
Patan city	15.15	1.8	31,000	2046	226,728	14,970
Patan vicinity	370	2.5	69,000	187	230,878	624
Patan district	385		100,000		457,606	1189
Bhaktapur city	6.56	4.7	25,000	3810	83,658	12,753
Bhaktapur vicinity	113	0.39	40,000	356	215,046	1903
Bhaktapur district	119		65,000		298,704	2510

The fatalities count comes from Rana (1935). The 1934 population estimate is deduced from the 1921 and 1942 census. The 2011 population is given for comparison and Kathmandu to nearly 5 % for the urban community of Bhaktapur. The high fatality rate in that urban community is of the same order of magnitude as the fatality rates recorded in the worst fatal meizoseismal areas which include the cities of Managua, Nicaragua, in 1972 (1 %), Spitak, Armenia, in 1988 (4.5 %), Avezzano and Messina, Italy, in 1915 and 1908 (17 and 20 %) (e.g., Nichols and Beavers 2003, 2008) and has to be compared to the 30 % recorded in 1976 in areas of the city of Tangshan, China, exposed to total collapse of masonry buildings (Shiono 1995).

This high fatality rate in Kathmandu valley is probably due to combined effects of the vulnerable multi-storys building stock, made of brick with mud mortar, its high concentration and of additional seismo-geological effects typical of the Kathmandu basin, including (1) very long solicitation of the structures due to trapping of the seismic waves (e.g., Bhattarai et al. 2012; Chamlagain and Gautam 2015), (2) dominant seismic periods, related to the seismic source and sedimentary basin response, corresponding to the natural periods of multi-storys buildings (e.g., Paudyal et al. 2012; Rajaure et al. 2014; Goda et al. 2015; Galetzka et al. 2015; Bhattarai et al. 2015) and (3) liquefactions (e.g., Gajurel et al. 2000; Mugnier et al. 2011). In comparison, mountainous areas of Bhojpur and Udaypur Gadhi fatality rates, on the hanging wall of the fault that ruptured, are of the order of one percent, which is low compared with the values observed in Kathmandu valley, but still very high for rudimentary buildings, wood-framed with light roof material, usually safer when, in addition, established on the bedrock.

When presented as a function of the distance to epicenter (Fig. 3), the earthquake fatality rate decreases in a similar way as the macroseismic intensity, not taking into account the most densely populated areas of the Kathmandu valley. Indeed, those regions appear as outliers, far beyond average fatality rates, even when considering separately the most urban areas and their vicinity (Fig. 4). In 1934, Patan was a mix of urban and rural environment, whereas Bhaktapur urban and rural zones were (and actually still are) very pure, an observation that help in understanding the differences between the urban and rural end members of each city. However, these fatality rates from these urban centers appear better correlated when plotted relatively to the building destruction rate (Fig. 5), suggesting a possible causal relationship between the fatality rate and the population density.

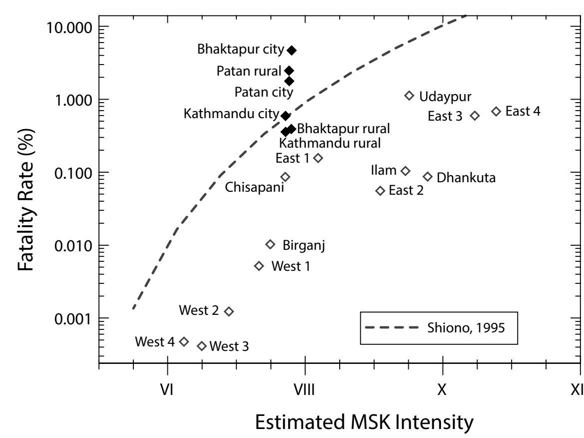

Fig. 4 Fatality rate from the 1934 Nepal–Bihar earthquake (Rana 1935) as a function of the mean MSK intensity from Ambraseys and Douglas (2004). The *black diamonds* correspond to the samples within the Kathmandu basin. The *dashed curve* corresponds to Shiono (1995) standard—unreinforced masonry—fatality rate relationship as a function of the macroseismic intensity

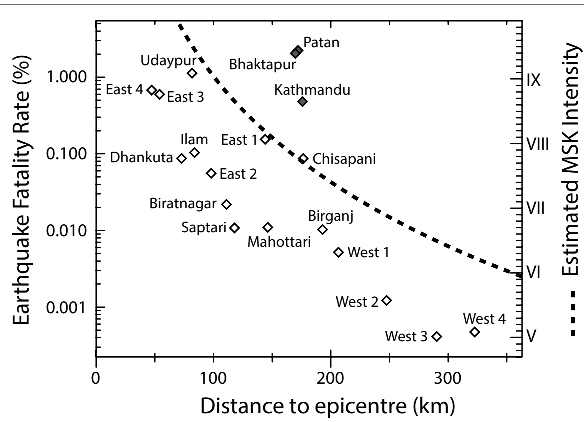

Fig. 3 Fatality rate from the 1934 Nepal–Bihar earthquake as a function of the distance to epicenter (Rana 1935). The *dashed curve* corresponds to the attenuation of the MSK macroseismic intensity from Ambraseys and Douglas (2004) as a function of the distance to epicenter. The *black diamonds* correspond to the samples within the Kathmandu basin

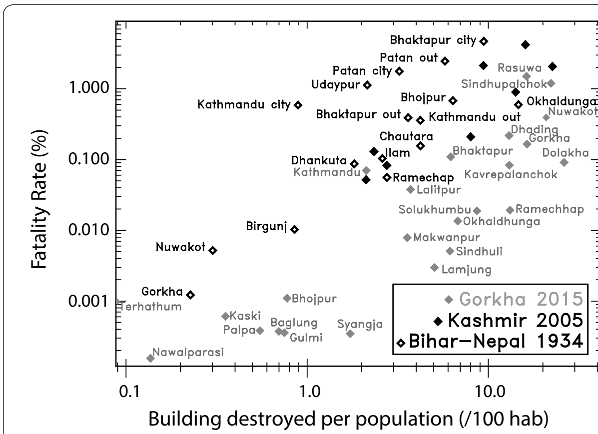

Fig. 5 Fatality rate from the 1934 Nepal–Bihar earthquake as a function of the building destruction (Rana 1935). The *black diamonds* correspond to the 1934 earthquake, the *red diamonds* to the 2015 Gorkha earthquake and the *blue diamonds* to the 2006 Muzaffarabad, Pakistan, earthquake (Maqsood and Schwarz 2011)

These fatality rates can already be used to derive first-order fatality estimates in the case of a repetition of the 1934 earthquake, assuming the local vulnerability has remained constant. For example, with the 2011 population census, we can calculate casualties in each zone used to calculate the 1934 fatality rates and reported in Table 1. Taking into account the change in administrative boundaries used in the recent census compared with 1934, we obtain numbers given in details in Additional file 1: Table S1. We then obtain 33,000 victims in Nepal, but over 50,000 in India. Due to the large increase in population in northern India, larger numbers of victims are expected in India, while the rupture zone remains in Nepal. If the 2001 census population is used instead, we obtain about 26,000 victims in Nepal and 39,000 in India. An interesting temporal variability can be observed when the 2001 and 2011 censuses are compared, beyond just the unavoidable increase in the number of victims. Population growth remains larger than 20 % per year in India, but is decreasing to values of the order of 14 % in Nepal. Hill districts of the epicentral zone of the 1934 earthquake tend to lose population, while Nepalese population dramatically increases in the foothills near the Indian border. Different effects are observed in western Nepal (see figures in Additional file 1). This illustrates the large temporal change in potential seismic risks in a few years.

The numbers of victims estimated above can only be considered as a baseline. Indeed, numerous effects complicate the problem. In addition to the population growth and redistribution, the fatality rates must have been modified by the change in population lifetime and the evolution of construction methods. The April 25, 2015, Gorkha earthquake definitely brings important new information to address these problems.

Comparison with the 2015 Gorkha earthquake

The earthquake of April 25, 2015 (Fig. 1), of magnitude M_w ~7.8 (M_L ~7.6), with more than 8700 victims, is the most deadly earthquake in Nepal since the M_w ~8.4 megaquake of 1934. Beyond the large number of victims, the destruction of infrastructure and houses was tremendous in the villages north of Kathmandu, even total in some locations, and a terribly traumatic situation was created for the population. While the epicenter was located near Gorkha city, the aftershock distributions covered a 150-km segment extending to the east (Adhikari et al. 2015). Fatality rates were moderate in the Katmandu Valley (<0.1 %), but was surprisingly large in hill districts north of Kathmandu, with a maximum fatality of 1.5 % in Rasuwa District, 1.2 % in Sindhupalchowk district and 0.4 % in Nuwakot district (Central Department of Statistics, Home Ministry, Nepal). When comparing the fatality rate with the building destruction rate per inhabitant (Fig. 5), the fatalities of the Gorkha earthquake appear significantly smaller than for the 1934 earthquake, while the building destruction rate appears comparatively large for the 2015 Gorkha earthquake. Actually, in some rural communities north of Kathmandu, the building destruction rate was close to 100 % in 2015. This suggests that large differences in some rural and some urban districts have now emerged in Nepal, with the implementation of appreciably efficient building methods in Kathmandu valley, while the construction methods were not improved at all since the 1934 earthquake in rural communities. Note that the 1934 and 2015 earthquakes both happened on a holiday around noon time.

The intensity distribution in the case of the Gorkha earthquake (Martin et al. 2015) hardly compares with predictions from known attenuation laws of the macroseismic intensity at short distance (the first tenths of kilometers) from the source. Nevertheless, to compare with the previous analysis for the 1934 earthquake, we use again the Ambraseys and Douglas (2004) attenuation law to estimate the intensities, taking into account an effective macroseismic epicenter north of Kathmandu in the center of the aftershock distribution. We note that the macroseismic intensities predicted by this attenuation law are significantly larger than what was observed for the Kathmandu valley (Martin et al. 2015), 10 to 30 km from the ruptured fault segment (e.g., Avouac et al. 2015; Grandin et al. 2015; Kobayashi et al. 2015). The fatality rates versus the estimated intensities (Fig. 6) are significantly smaller than the values

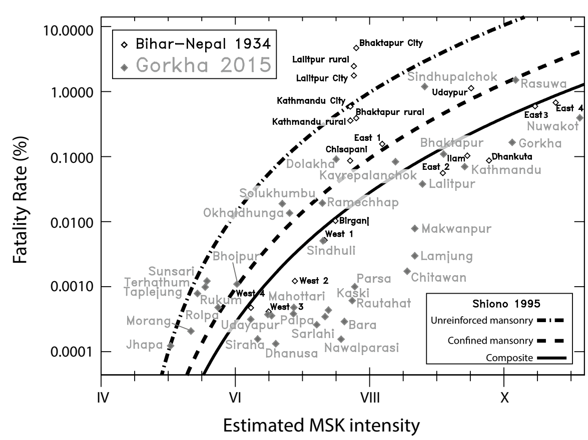

Fig. 6 Fatality rate from the 1934 Nepal–Bihar earthquake (Rana 1935) as a function of the mean MSK intensity estimated from Ambraseys and Douglas (2004). The *black diamonds* correspond to the 1934 earthquake and the *red diamonds* to the 2015 Gorkha earthquake. The *full lines* correspond to the scaling laws proposed by Shiono (1995). See text for discussions on the biases—significant for the Kathmandu valley—introduced by the "estimated MSK intensity" reference frame

observed for the 1934 earthquake. This conclusion still hold after converting the estimated intensities in true intensities at observation sites documented both in 1934 and 2015, respectively, in Martin and Szeliga (2010) and Martin et al. (2015). In Fig. 6, scaling laws proposed by Shiono (1995) are also shown versus intensity. While the large heterogeneity mentioned before causes large scatter in the case of the Gorkha earthquake (e.g., intensities reported in Kathmandu valley typically range from I_{EMS98} 6 to 8), the so-called composite building Shiono scaling law appears on average as a satisfactory description of the 2015 data.

Conclusions

In this paper, complementing previously known information, the censuses carried out in 1921 and 1942 in Nepal are used to evaluate the fatality rates from the great 1934 Bihar–Nepal earthquake and better characterize its impact in eastern Nepal. Such data provide important archives, given the scarcity of documented magnitude 8 earthquakes. While rarely exceeding 1 %, even in the most impacted areas of eastern Nepal, close to the epicenter and on the hanging wall of the thrust fault that was activated, the fatality rates exceed 0.5 % in Kathmandu valley, reaching even 5 % in urban Bhaktapur. Such observed fatality rates can be used to broadly estimate their order of magnitude in case this earthquake repeats. While the numbers obtained have to be taken with caution, they definitely illustrate that the country has to consider preparations. The order of magnitude of temporal variations (+15 % per decade) noted when using 2001 or 2011 population numbers, and the fact that larger numbers of victims have now to be expected on the India side, are probably robust.

Compared with the fatality rates of the 1934 earthquake, the fatalities of the 2015 earthquake are significantly smaller for a given estimated intensity, except in some hill districts. This suggests that the lessons of the 1934 earthquake may have been ignored in some rural districts and that earthquake prevention methods have not been widely implemented outside the Kathmandu valley. This is also illustrated by the fact that the composite Shiono scaling law (Shiono 1995), which reflects the building prevention strategies suggested in Asia after the 1976 Tangshan earthquake in China, appears to reproduce, on average, the 2015 fatality rates, while the scaling law for unreinforced masonry reproduces the 1934 earthquake. Therefore, while numerous problems remain open, the results of decades of earthquake prevention methods, indeed, seem to have saved a significant number of lives in 2015. In the absence of more precise work, the composite Shiono scaling law could be a reasonable approach to estimating casualties in the case of contemporary large Himalayan earthquakes.

While simple scaling laws, in no way, can be claimed as reliable predictive models, they suggest important features that can be used to guide further research. In any case, given the large increase in population crowding in buildings, which are built both in Nepal and in India without much consideration for earthquake hazards (e.g., Dixit et al. 2013), it is the duty of the scientific community to raise great concern in this matter, and to make sure that every possible steps are taken to mitigate the effects of the coming megaquake in the Himalayan foothills. Intensity and fatality distributions from the 2015 Gorkha earthquake, while referring to a smaller earthquake and probably of a different kind, will be of tremendous importance to better constrain possible fatality scaling laws, and the potential damage and loss of life from the next giant Himalayan earthquake.

Additional file

Additional file 1: Text S1. Biography of Brahma Shamsher Rana (December 1909–January 1989) Personal communicationwith Sagar Shamsher Janga Bahadur Rana (Nephew of Brahma Shamsher). **Table S1.** Fatalities count per district due to a repetition of the January 15th, 1934 earthquake in 2001 and in 2011, applying the fatality rates observed in 1934. The population is the divisions used in 1934 are estimated using the 2001 and 2011 census data (Central Bureau of Statistics). **Table S2.** District name equivalence between Rana (1935) and present-day districts names. **Figure S1.** Map of eastern nepal districts showing an estimate of the population derived from 1921 and 1942 census (green in thousands), the number of fatalities (red) (and the number of collapsed buildings (violet) (Rana, 1935). **Figure S2.** Map of the fatality rates (this study) and damages mentioned in Rana 1935. MSK VIII isoseist from this study. **Figure S3.** Population distribution in 2011 according to the 2011 Census. **Figure S4.** 2001 to 2011 trends in population distribution. Source: census 2001 and 2011.

Authors' contributions

The material of this paper is part of the doctoral thesis of SNS, defended in 2011 at IPGP. All three authors contributed to the data analysis and manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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