LESSONS OF 2015 NEPAL EARTHQUAKE DISASTER

A Short Report on Effects of

7.8 M_w Earthquake of 25 April 2015 and Its Aftershocks

(Including Photo Documentation)

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Acknowledgement:
The figures and the information presented in this report have been taken from various publicly available sources. The credits and references are given as far as possible.

Photo credits:
All the photos were taken by the author Sujan Malla, except Photo 2 (left), Photo 3 (left), Photo 4 (upper) and Photo 6 (left).

Cover photo by Sujan Malla:

Collapsed buildings on the Swayambhu hill after the earthquake of 25 April 2015

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Appendix: Photo documentation of effects of 7.8 M_w earthquake of 25 April 2015

1 General introduction

When the 7.8 M_w earthquake struck on 25 April 2015 (Saturday), the author was with his family at the Safari Narayani Hotel on the bank of the Rapti river bordering the Chitwan National Park in south Nepal. Although the ground shaking lasted there for more than one minute, it was relatively moderate and did not cause any visible structural damage.

As the main highway via Mugling was blocked by a massive landslide, the author returned to Kathmandu via the old and winding Tribhuvan Highway two days after the main shock. Along the highway, there were many small and large rockfalls (see Photo 1) and also the first collapsed stone masonry buildings could be seen (see Photo 19 and Photo 20). After arriving in the Kathmandu Valley, the author went around the three main cities of Kathmandu, Lalitpur (Patan) and Bhaktapur to make a photo documentation of the earthquake damage to buildings and historical structures.

In this short report (which should be considered as a discussion paper), some lessons are drawn and some questions are raised based on the author's personal observations and discussions with many people in Nepal. The appendix at the end of the report contains the author's photo documentation of the damage caused by the main shock of 25 April 2015. It consists of a selection of the photos taken by the author from 27 April to 1 May 2015, prior to possible further damage by the strong aftershock of 12 May 2015. This report will hopefully make a small contribution towards the improvement of the disaster preparedness in Nepal before the next big earthquake arrives.

2 Brief history of earthquake disasters in Nepal

Major seismic events are not new to Nepal. The most devastating earthquakes in the recorded history of Nepal are as follows (Bilham, 2004; Newar, 2004; Gahalaut, 2009; Rajendran et al., 2013; Srivastava et al., 2013):

- 7 June 1255 AD (~8.0+ M): This was the first and possibly the deadliest earthquake disaster documented in the Nepalese history. About 30,000 people (30% of the total population of around 100,000) were killed in Kathmandu, including King Abhaya Malla. There were aftershocks for about three years.
- 6 June 1505 AD (~8.2 M): The approximately 600 km long rupture zone of this extremely strong event extended across the western half of Nepal. This earthquake caused widespread destruction in west Nepal, India and south Tibet.
- 26 August 1833 AD (~7.8 M): Two major shocks caused a lot of devastation in the Kathmandu valley. The first one was felt at about 6 p.m. and the second one followed at about 11 p.m. at night.
- 16 January 1934 AD (8.0 M_w) : The “Great Nepal-Bihar Earthquake” caused a large number of buildings and heritage structures to collapse. This disaster killed about 17,000 people in Nepal and India, out of which around 4,500 died in the Kathmandu Valley.

The estimated epicenters of these seismic events are shown in Fig. 1. Other significant earthquakes in the history of Nepal occurred in 1260, 1408, 1681, 1767, 1810, 1869, 1916, 1980, 1988 and 2011 AD.

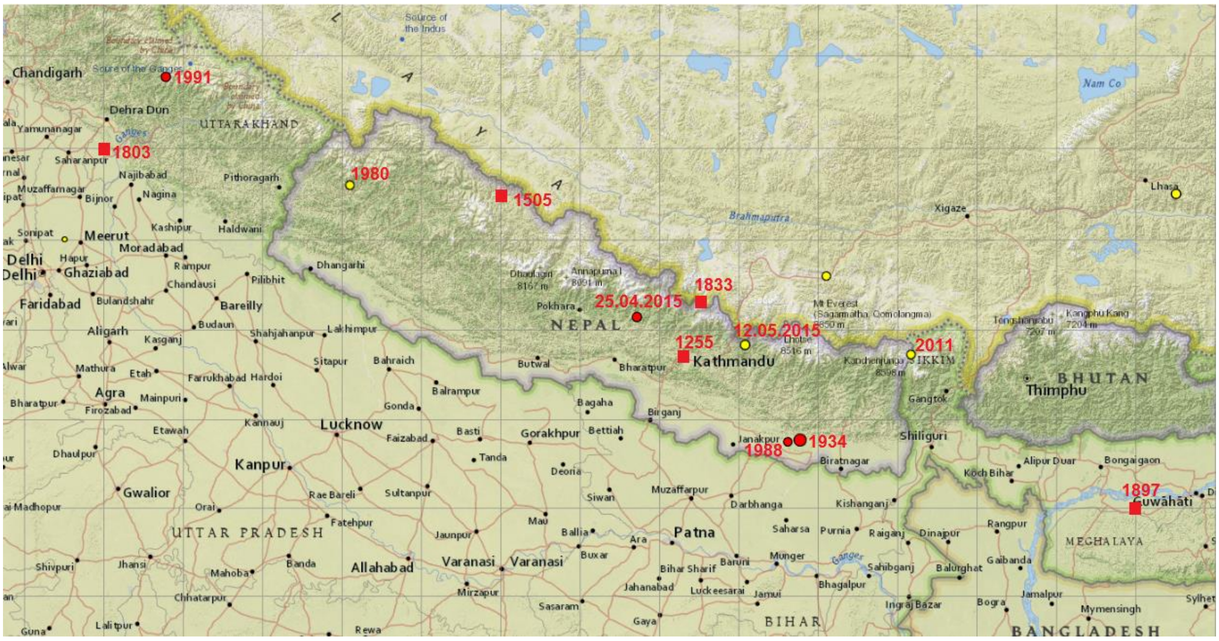

Fig. 1 Epicenters of significant earthquakes in central Himalayan region based on data from NCEI (2015), Rao et al. (2006) and Gahalaut (2009) (base map with epicenters of earthquakes since 1900 prepared with NCEI Natural Hazards Viewer; yellow circles: earthquakes since 1900 with fatalities exceeding 100, but not exceeding 1000; red circles: earthquakes since 1900 with more than 1000 fatalities; red squares: estimated epicenters of historical earthquakes prior to 1900 added by the author)

3 Earthquake series of April-May 2015

The epicenter of the main shock of 25 April 2015 with a magnitude of 7.8 M_w was located at the village of Barpak in the Gorkha district, due to which it is also referred to as the Gorkha earthquake. When such a strong seismic event occurs, aftershocks usually last for several weeks and even months until a frictional equilibrium is re-established in the rupture zone. Although the frequency of the aftershocks generally decreases with time, this process is by no means smooth and continuous. For instance, aftershock frequency significantly increased again after the thus far strongest aftershock of magnitude 7.3 M_w on 12 May 2015.

As shown in Fig. 2, the epicenters of the main shock and the numerous aftershocks are distributed over an approximately rectangular area having a length of around 180 km roughly parallel to the Himalayan range and a width of around 65 km. It extends from the eastern part of the Lamjung district to the western part of the Dolakha district, with Kathmandu located in the middle near the southern boundary of this area.

While the epicenters of the main 7.8 M_w shock of 25 April 2015 and a strong 6.6 M_w aftershock, which occurred about half an hour after the main shock, are both in the Gorkha district near the western end of the rupture zone, the strongest aftershock of 12 May with a magnitude of 7.3 M_w and the next strongest 6.7 M_w aftershock of 26 April had their epicenters in the Dolakha and Sindhupalchok districts, respectively, about 130 km to the east of the epicenter of the main shock.

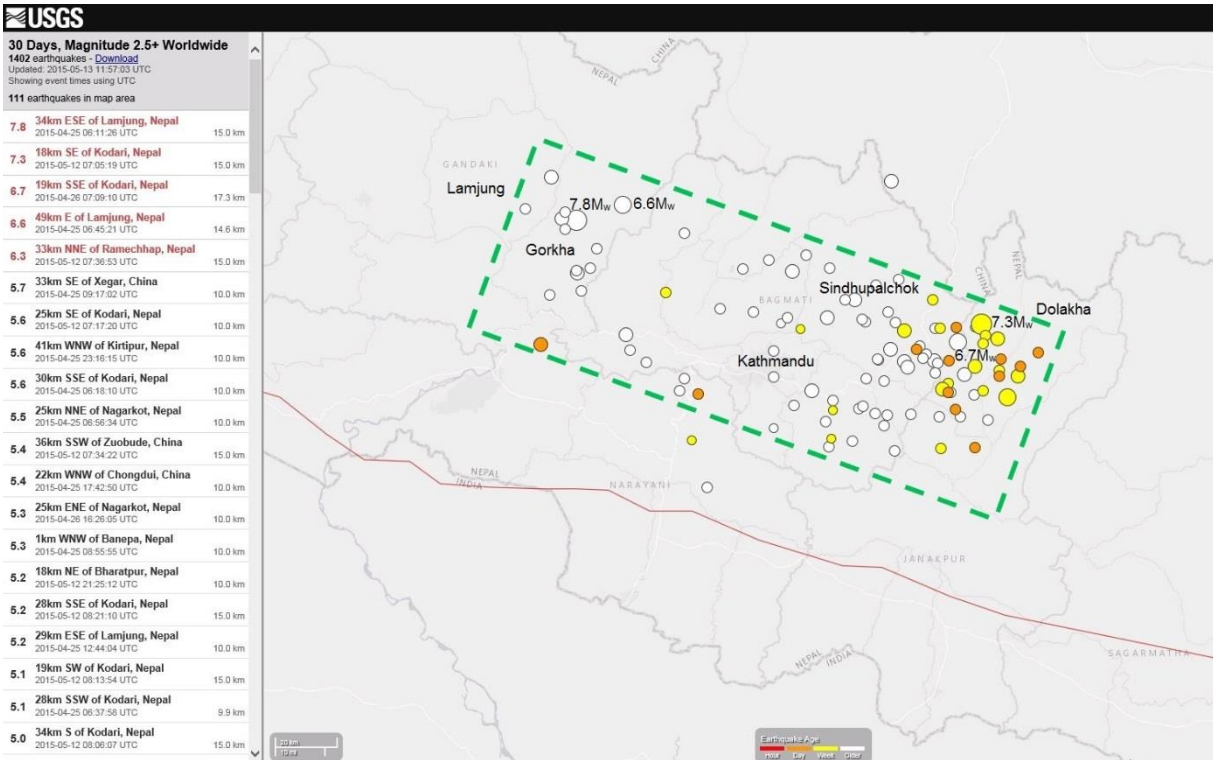

Fig. 2 **Epicenters of main shock and aftershocks of 2015 Nepal earthquake series (data and plot as of 13.05.2015 11:57 UTC obtained from the website of USGS Earthquake Hazards Program, Latest Earthquakes; dashed green rectangle added by the author)**

It is worthwhile to quote here the following statement from the Wikipedia article on aftershocks (http://en.wikipedia.org/wiki/Aftershock, ver. 14.05.2015):

"Most aftershocks are located over the full area of fault rupture and either occur along the fault plane itself or along other faults within the volume affected by the strain associated with the main shock."

Thus, the rectangular area marked by a green dashed line in Fig. 2 would show approximately the extents of the rupture zone of this earthquake. The available information suggests that a slip of up to about 4 m occurred on the nearly horizontal main (or sole) Himalayan fault, which is a continuation of the main frontal thrust (MFT) fault, as illustrated in Fig. 3.

The resulting ground displacements that occurred during the main shock of 25 April 2015 were computed by a team of Caltech and JPL scientists based on a combination of satellite radar imaging data and GPS data (McKinney, 2015). These displacements are plotted in Fig. 4, which shows that Kathmandu shifted by around 2 m towards the south and rose by about 1 m during the main shock.

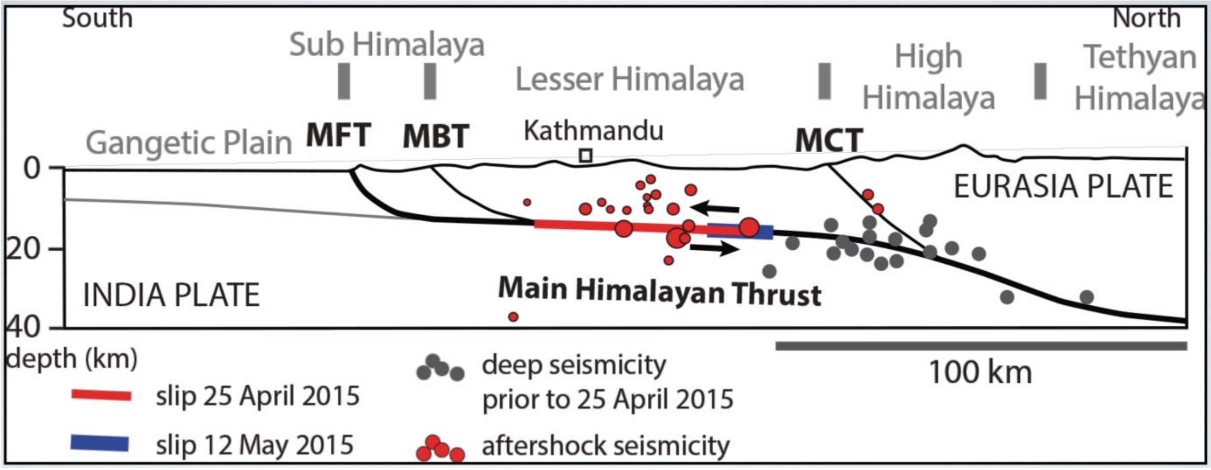

Fig. 3 Major faults in the Himalayan region and rupture zones of earthquakes of 25 April 2015 and 12 May 2015 as shown by USGS (2015a) on a generalized cross-section after Lavé and Avouac (2000) and Kumar et al. (2006) (MFT: main frontal thrust; MBT: main boundary thrust; MCT: main central thrust)

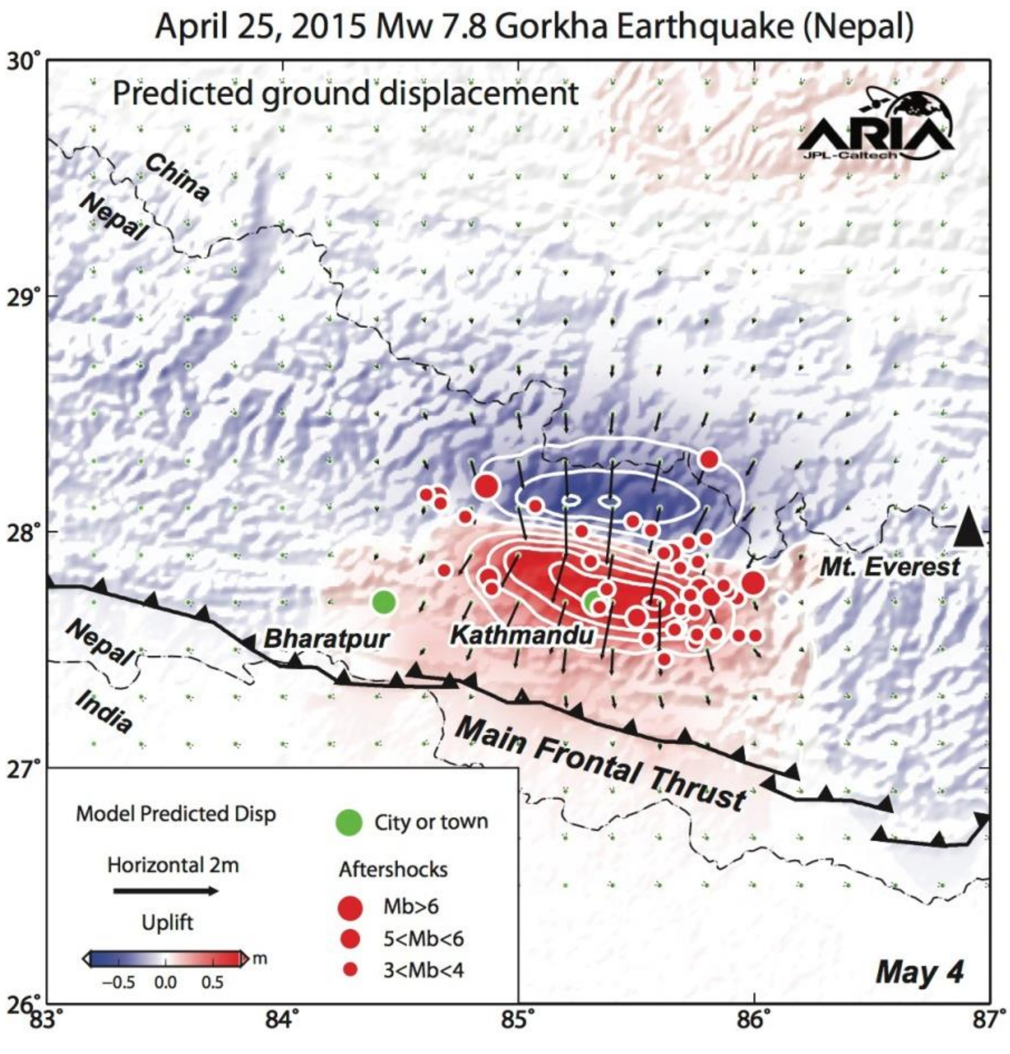

Fig. 4 Horizontal and vertical ground displacements caused by 7.8 M_w main shock of 25 April 2015; blue and red shades represent vertical ground displacements and scaled arrows indicate directions and amounts of horizontal ground displacements (figure credit: NASA/JPL-Caltech; see McKinney, 2015)

4 Epicentral distance and attenuation laws

Prior to this earthquake, the author had not paid much attention to the fact that an epicenter is by definition just a point on the ground surface vertically above the location (hypocenter) on the causative fault, where the rupture or slip displacement initiates, triggering an earthquake. As an earthquake unfolds, the rupture propagates across an area of the fault. The rupture zone of a strong earthquake could be very large and its epicenter may not even be at the middle of this zone, as in the case of the main shock of 25 April 2015 with the epicenter at the western end of the rupture zone.

There is a widely held notion among the general public that the intensity of ground shaking and hence the destructive power of an earthquake generally decreases as the epicentral distance increases. Thus, when a strong earthquake occurs, the location of the epicenter gets a lot of attention in the press, with the earthquake location often depicted on a map as concentric circles around the epicenter. This way of thinking may be also related to the fact that many traditional attenuation laws, or ground-motion prediction equations (GMPE), are empirical relationships to represent a continuous reduction of the intensity of ground motion with an increasing epicentral distance, implicitly assuming seismic waves to originate from a point source. Such a model would be applicable only when the rupture zone is relatively small, i.e. when the magnitude of an earthquake is not very high.

When a strong earthquake is caused by a dip-slip movement on a large and almost horizontal fault, as in the case of the main shock of 25 April 2015, the epicentral distance is not a very relevant parameter for the determination of the ground motion, because a large portion of the affected area lies even directly above the rupture zone. Seismic waves arrive at a given point from the whole of the rupture zone and not just from the epicenter. This explains why the damage caused by the main shock of 25 April 2015 did not decrease with an increasing epicentral distance, as evident from the intensity map shown in Fig. 5. In fact, the largest damage and loss of lives occurred in the Sindhupalchok district, about 100 km to the east of the epicenter in Gorkha.

Another example is the great Nepal-Bihar earthquake of 1934, which caused massive destruction in the Kathmandu Valley, although the epicenter was about 120 km away. Many people attributed the strong shaking in the Kathmandu Valley primarily to the local dynamic amplification in the thick sediment layer (lake deposits). As illustrated in Fig. 6, the estimated rupture zone of the 1934 earthquake was indeed huge and the Kathmandu Valley was in fact within this zone (Pandey and Molnar,1988; Avouac et al., 2001; Chamlagain, 2009).

The Wikipedia article on epicenters mentions also an interesting example of the 7.9 M_w Denali earthquake of 2002 in Alaska, whose epicenter was at the western end of the rupture zone, but the greatest damage occurred about 330 km away at the eastern end of the rupture zone (see http://en.wikipedia.org/wiki/Epicenter, ver. 15.05.2015).

It is thus clear that the attenuation laws employing the epicentral distance as a parameter should not be used in an earthquake hazard analysis in the Himalayan region, as the rupture zone of a strong seismic event in this region tends to be large and almost horizontal. It is necessary to resort to a more modern attenuation law that uses the minimum distance from the causative fault as a parameter. There could still be a research need to develop or refine a representative attenuation model suitable for an earthquake hazard analysis in this region.

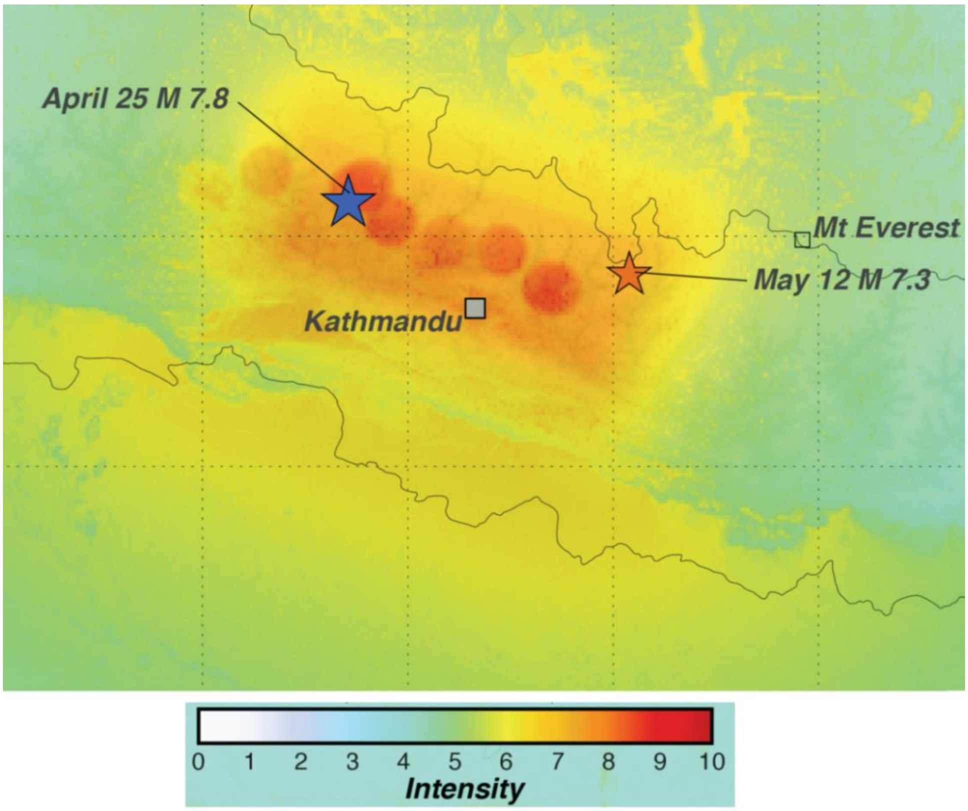

Fig. 5 Intensity of ground shaking produced by 7.8 M_w main shock of 25 April 2015 (figure credit: USGS, 2015a)

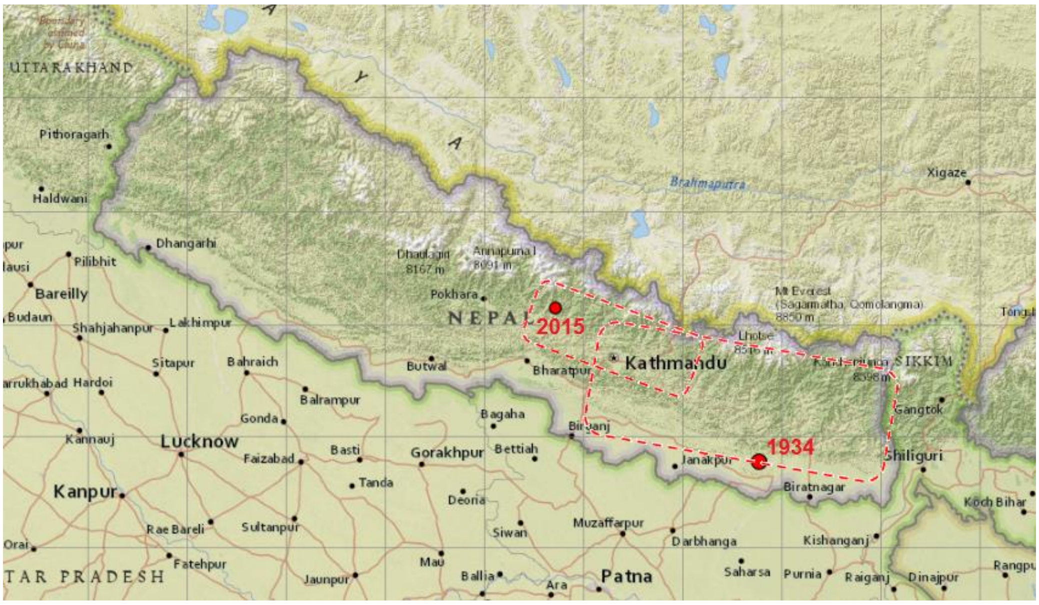

Fig. 6 Rupture zones of 8.0 M_w earthquake of 1934 and 7.8 M_w earthquake of 2015 (base map with epicenters prepared with NCEI Natural Hazards Viewer; dashed red rectangles added by the author to approximately indicate the rupture zones)

5 Aftershocks and foreshocks

It is worthwhile to compare the magnitudes of foreshocks and aftershocks of other major earthquakes, since worries about this issue are still widespread among the people in Nepal affected by the 7.8 M_w earthquake of 25 April 2015 and its numerous aftershocks. In particular, the very strong 7.3 M_w aftershock of 12 May 2015 unnerved the people, just when life was almost returning to normal again. There have also been persistent rumors that the earthquake of 25 April 2015 could be just a foreshock of an even more devastating earthquake with a magnitude exceeding 8.0 or even approaching 9.0. Some seismologists told the media that the estimated fault slip of the earthquake of 25 April 2015 released only about 25% the accumulated strains in the causative fault (for example, see Oskin, 2015). Sometimes criminal elements deliberately spread rumors, for example, saying “US scientists have predicted that a magnitude M 8.5+ event will strike tomorrow at about 6 p.m.". Such rumors could in some cases be traced back to certain gangs of thieves, a few of whom were even arrested and shown on television in Nepal.

In fact, it is quite normal that a strong earthquake is followed by aftershocks for a considerable length of time after the main shock. Aftershocks may occur on the causative fault itself if some regions of this fault did not slip sufficiently during the main shock or they may also result from rupturing of secondary faults disturbed by the slip displacement on the primary fault during the main shock.

The magnitudes of the main shock and the strongest aftershock of some recent earthquakes in various parts of the world are compared in Table 1. The magnitude difference between the main shock and the strongest aftershock of these earthquakes varies from 0.5 to 1.1. In the case of the 2015 Nepal earthquake, the difference was 0.5, which would be at the lower end of this range.

Table 1 Main shocks and aftershocks of some recent earthquakes (source: Wikipedia)

Earthquake	Date	Magnitude of main shock	Strongest aftershock magnitude (time of occurrence)	Magnitude difference*
Tangshan, China	28.7.1976	7.8 M_L	7.1 M_L (16 hours later)	0.7
Northridge, USA	17.1.1994	6.7 Mw	6.0 M_w (1 minute later) 6.0 M_w (11 hours later)	0.7
Indian Ocean	26.12.2004	9.1 Mw	8.6 M_w (Sumatra earthquake of 28.3.2005)	0.5
Haiti	12.1.2010	7.0 Mw	5.9 M_w (about 80 minutes) 5.9 M_w (20.1.2010)	1.1
Christchurch, New Zealand	4.9.2010	7.1 Mw	6.3 M_L (22.2.2011) 6.3 M_L (13.6.2011)	0.8
Tohoku, Japan	11.3.2011	9.0 Mw	7.9 M_w (29 minutes later)	1.1
Nepal	**25.4.2015**	**7.8 Mw**	**7.3 M_w (on 12.5.2015)**	**0.5**

* Local magnitude M_L and moment magnitude M_w are taken as equivalent for the calculation of this difference.

The 7.8 M_w earthquake of 25 April 2015 arrived without any significant foreshock or precursor. In rare cases, a strong earthquake could itself be just a foreshock of an even bigger devastating earthquake later on. All but one of the examples of earthquakes with strong foreshocks, as listed in Table 2, are from New Zealand. In all of the events in New Zealand, the strong foreshocks occurred either on the same day or up to 2 days prior to the main shock. The most disturbing case, however, is that of the 2002 Sumatra earthquake with a magnitude of 7.3 M_w, considered to be the foreshock of the massive 2004 Indian Ocean earthquake having a magnitude of 9.1 M_w, which occurred two years later causing also a catastrophic tsunami disaster.

Table 2 Examples of some earthquakes with strong foreshocks (source: Wikipedia)

Earthquake	Date	Magnitude of main shock	Strongest foreshock magnitude (time of occurrence)
Hanmer Springs, New Zealand	22.5.1948	6.2 M_L	5.9 M_L (earlier on the same day)
Raoul Island, New Zealand	15.1.1976	8.2 M_w	7.8 M_w (earlier on the same day)
Buller Ranges, New Zealand	29.1.1991	6.3 M_w	6.1 M_w (one day earlier)
Indian Ocean	26.12.2004	9.1 M_w	7.3 M_w (2002 Sumatra earthquake, which occurred about 2 years earlier on 2.11.2002)
Cook Strait, New Zealand	21.7.2013	6.5 M_w	5.7 M_w (two days earlier) 5.8 Mw (earlier on the same day)

In short, a very strong foreshock with a magnitude of the order of 7.8 M_w is quite rare and in many known cases with strong foreshocks, the main shock followed soon afterwards, within about 2 days after the foreshock. Therefore, the probability that the 7.8 M_w earthquake of 25 April 2015 would be followed by an even more devastating event within a few months or years appears to be quite low. However, it can unfortunately also not be ruled out completely, as evident from the example of the 2004 Indian Ocean earthquake and the results of a probabilistic aftershock analysis by USGS (2015b) shown in Table 3.

Table 3 Results of probabilistic aftershock analysis for 7.8 M_w earthquake of 25 April 2015 (USGS, 2015b)

Time period	Magnitude range of aftershocks	Most likely number of aftershocks (95% confidence)	Probability of one or more aftershocks
1 month (from 27 May 2015 to 26 June 2015)	M5.0 to M6.0	0 to 5	62%
	M6.0 to M7.0	0 to 1	10%
	M7.0 to M7.8	*	1%
	M ≥ 7.8	*	0.2%
1 year (from 27 May 2015 to 26 May 2016)	M5.0 to M6.0	0 to 12	92%
	M6.0 to M7.0	0 to 2	25%
	M7.0 to M7.8	0 to 1	3%
	M ≥ 7.8	*	0.6%

6 Strong-motion records from Kathmandu

6.1 Record of 7.8 M_w main shock

It is unclear how many strong-motion stations exist in Nepal and which of them actually functioned during the main shock and several strong aftershocks of the 2015 earthquake series. All records publicly available on the internet are from a single USGS strong-motion station in Kathmandu located at Kanti Path within a compound belonging to the US embassy, which is across the street from the Election Commission Building (Bahadur Bhawan) and to the south of the Narayanhiti Palace.

The plots of the time histories of the 3 components of the ground acceleration recorded during the 7.8 M_w main shock of 25 April 2015 and the corresponding elastic response spectra for 5% damping obtained from the website www.strongmotioncenter.org of the Center for Engineering Strong Motion Data are shown in Fig. 7 (CESMD, 2015). The peak ground acceleration (PGA) of each horizontal component was about 0.16 g and the vertical PGA was around 0.19 g.

The elastic response spectra of the horizontal components of the ground motion during the main shock have a central period in the range of about 4 s to 5 s, which apparently corresponds to the fundamental natural period of the thick soil layer with a thickness of up to about 500 m covering the Kathmandu Valley. If that would be the case, the fundamental frequency of the thick soil layer undergoing large amplitude vibrations produced by the main shock would be around 0.2 Hz, which is a very low value indeed. In the long period range from about 3.5 s to 8.0 s, the spectral accelerations due to the main shock are up to two times higher than the design elastic response spectrum according to UBC for soil type S2 in zone 4 (see Fig. 7).

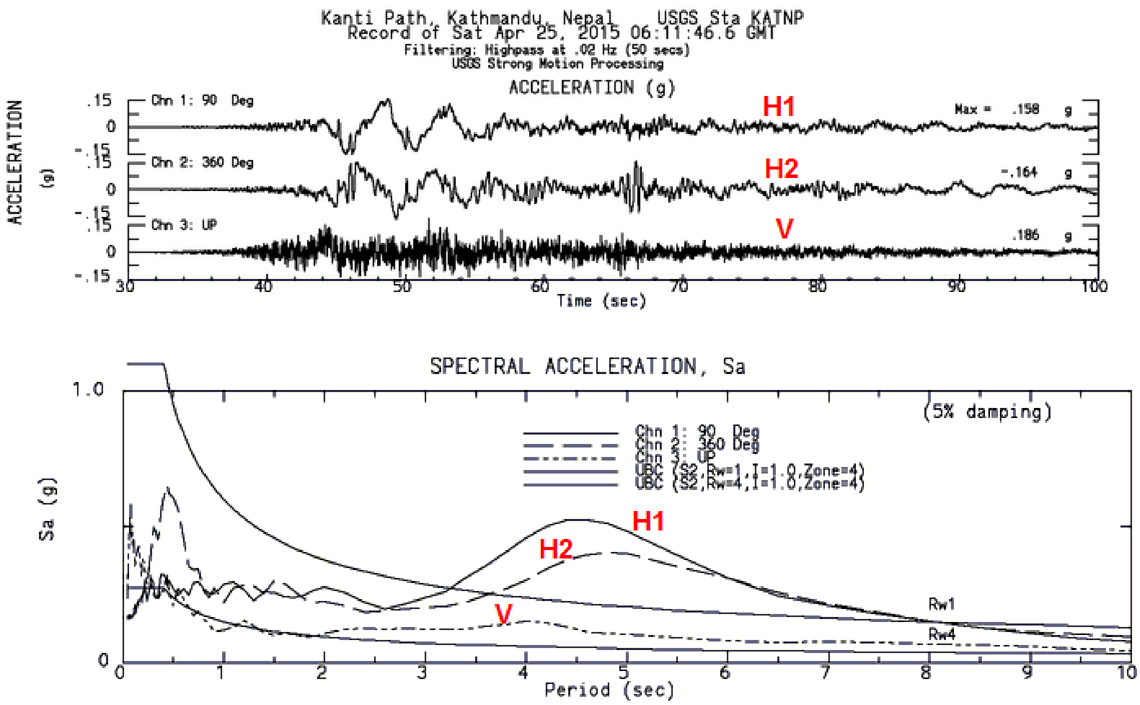

Fig. 7 **Acceleration time histories and elastic response spectra for 5% damping of 3 components of ground motion recorded during the 7.8 M_w main shock of 25 April 2015 at the Kanti Path strong-motion station in Kathmandu (H1, H2: horizontal components, V: vertical component; figure credit: USGS/CESMD)**

In Fig. 8, the time histories of acceleration, velocity and displacement are shown for the horizontal component H1 of the ground motion recorded at the Kanti Path station during the main shock, as available in the PEER Strong Motion Database as of 26 May 2015. The filter parameters appear to differ from those employed by CESMD for the plots shown in Fig. 7.

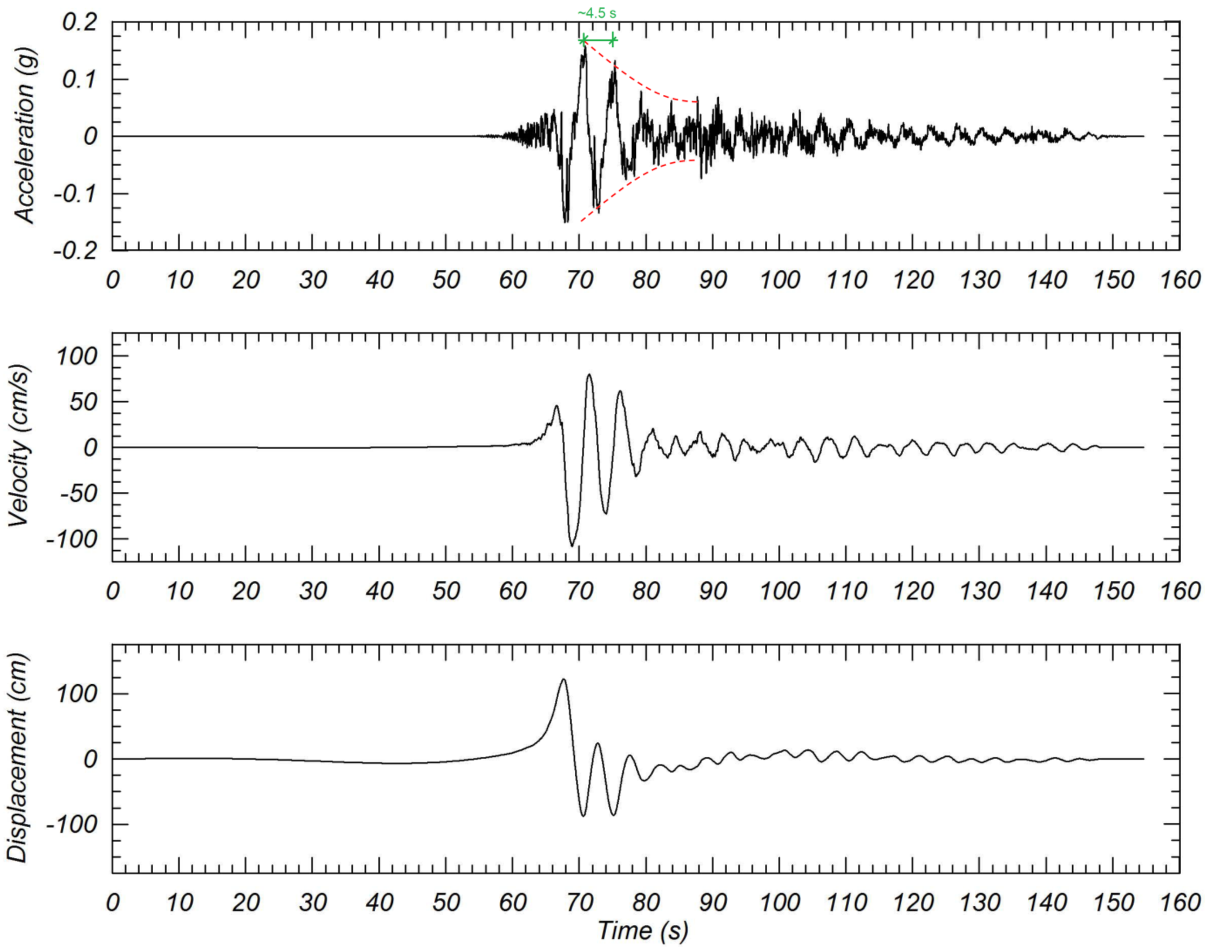

Fig. 8 **Time histories of acceleration, velocity and displacement in the case of the horizontal component H1 recorded at the Kanti Path strong-motion station in Kathmandu during the main shock (figure credit: PEER Strong Motion Database; data from USGS KATNP station; filter parameters appear to differ from those used for the plots of Fig. 7 prepared by CESMD; the author has added red dashed lines to mark what appears to be a damped free vibration phase and indicated in green a peak spacing of about 4.5 s apparently corresponding to the fundamental period of the soil layer)**

The strong-motion record shown in Fig. 8 has following interesting features:

- The large-amplitude cycles of the horizontal ground motion could be broadly interpreted as the low-frequency (i.e. long-period) damped free vibration response of the thick soil layer in Kathmandu following an initial slip displacement of the causative fault.
- After about 4 cycles of the large amplitude damped vibrations, at least two further smaller excitations seem to have occurred, causing the amplitude to increase again, followed each time by what appears to be a damped free vibration response.
- In certain sectors of the acceleration time history, the dominant low-frequency motion is almost overshadowed by high-frequency contents, which are presumably due to different types of seismic waves arriving from various portions of the rupture zone.
- The displacement time history obtained by a double integration of the acceleration recorded in Kathmandu during the earthquake of 25 April 2015 shows that the largest amplitude of the displacement cycles was of the order of 1 m in both horizontal components.

- As the Kathmandu Valley actually shifted towards the south during the earthquake, the displacement time history should actually show a non-zero end value. This is, however, not the case in Fig. 8, as the residual displacement was apparently removed in the numerical processing of the recorded data. According to the information received through Malhotra (2015), the ground motion records from Kathmandu will most probably be reprocessed by USGS to include the residual displacements, but that is not likely to affect the structural response.

The fundamental horizontal natural frequency of a soil layer is given by

$$f = \frac{v_s}{4H} \tag{1}$$

where H is the thickness of the soil layer and v_s is the shear wave velocity, which can be expressed in terms of the dynamic shear modulus G and the mass density ρ as follows:

$$v_s = \sqrt{\frac{G}{\rho}} \tag{2}$$

If the soil layer in the area of the recording station is assumed to have a thickness of H = 400 m and the fundamental natural frequency is taken as f = 0.22 Hz (i.e. period T = 4.5 s), the average value of the shear wave velocity would be v_s = 350 m/s according to Eq. (1). If the mass density is taken as ρ = 1800 kg/m^3, a rough estimate of the dynamic shear modulus of the whole soil layer would be obtained as G = 220 MPa using Eq. (2). These very rough estimates of the shear wave velocity and the dynamic shear modulus are quite plausible mean values for the thick soil layer in Kathmandu.

It should be noted that the dynamic shear modulus and hence the shear wave velocity usually increase with depth as the confining stress increases. The shear wave velocity in Kathmandu probably varies from around 100 m/s near the ground surface to about 500 m/s at the bottom of the soil layer. Moreover, the dynamic shear modulus of a soil is strain-dependent, for example as illustrated in Fig. 9 (Seed and Idriss, 1970; Vucetic and Dobry, 1991). Thus, the effective dynamic shear modulus for large-amplitude vibrations during a strong earthquake would be significantly smaller than the one for small-amplitude vibrations produced by smaller events, such as the aftershocks.

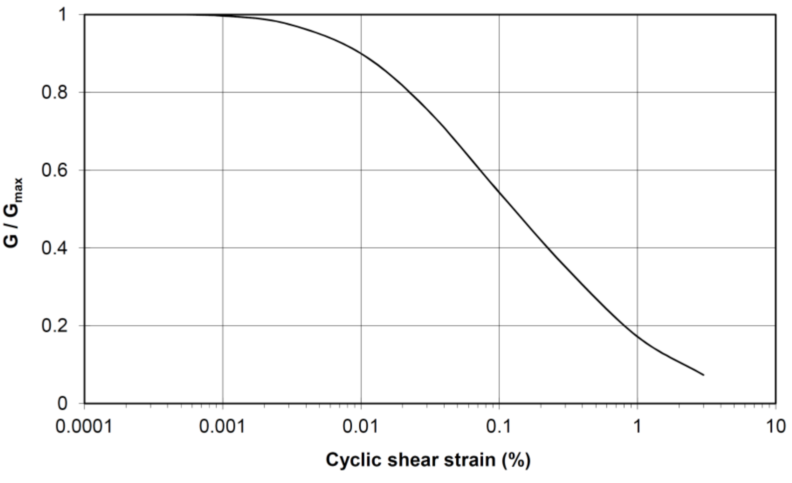

Fig. 9 Strain-dependence of dynamic shear modulus G (example showing the mean curve for a clayey soil with a plasticity index in the range of 20 to 45; G_{max}: maximum dynamic shear modulus, i.e. shear modulus for very small amplitude motions)

6.2 Records of aftershocks

The ground accelerations due to the 6.6 M_w aftershock of 25 April 2015 and the 7.3 M_w aftershock of 12 May 2015 are illustrated in Fig. 10 and Fig. 11, respectively. The peak ground accelerations (PGAs) of the strongest aftershocks are compared with those of the main shock in Table 4.

In the case of the aftershocks, the low-frequency component representing the dynamic response on the soil layer appears to have a central period of less than 4 s. This is possibly due to the higher dynamic stiffness of the soil subjected to smaller amplitude vibrations (see Fig. 9).

Table 4 Comparison of peak ground accelerations (PGAs) due to the main shock and the strongest aftershocks

Earthquake	Peak ground acceleration (PGA)		
	Horizontal component H1	Horizontal component H2	Vertical component V
7.8 M_w main shock of 25 April 2015	0.158 g	0.164 g	0.186 g
6.6 M_w aftershock of 25 April 2015	0.047 g	0.046 g	0.045 g
6.7 M_w aftershock of 26 April 2015	0.054 g	0.065 g	0.038 g
7.3 M_w aftershock of 12 May 2015	0.072 g	0.087 g	0.075 g

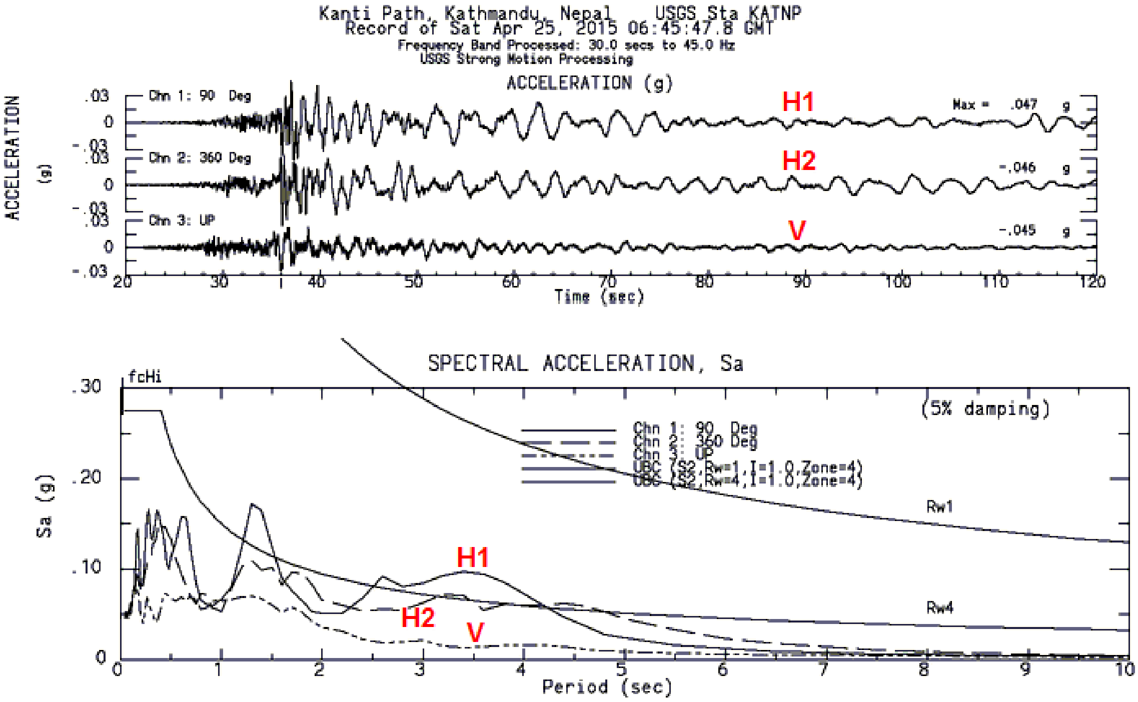

Fig. 10 Acceleration time histories and elastic response spectra for 5% damping of 3 components of ground motion recorded during the 6.6 M_w aftershock of 25 April 2015 at the Kanti Path strong-motion station in Kathmandu (H1, H2: horizontal components, V: vertical component; figure credit: USGS/CESMD)

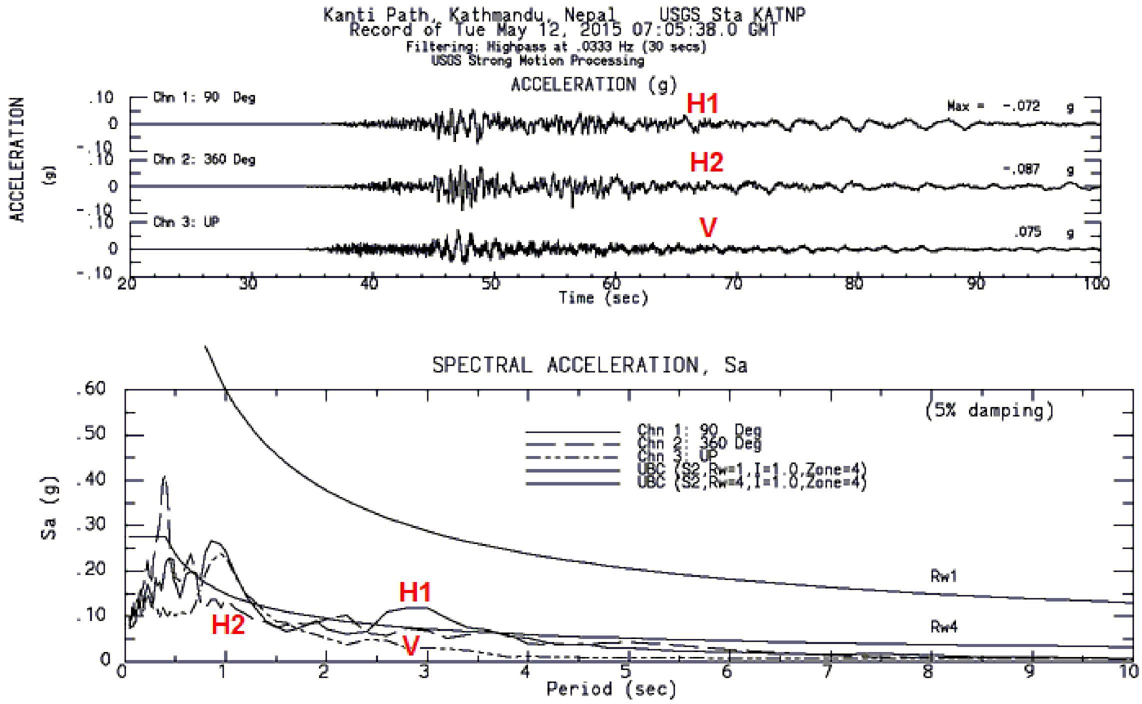

Fig. 11 **Acceleration time histories and elastic response spectra for 5% damping of 3 components of ground motion recorded during the 7.3 M_w aftershock of 12 May 2015 at the Kanti Path strong-motion station in Kathmandu (H1, H2: horizontal components, V: vertical component; figure credit: USGS/CESMD)**

7 Observations about earthquake damage to structures

7.1 Earthquake damage to temples and heritage structures

The earthquake of 25 April 2015 had a devastating effect on the ancient temples and heritage structures (see Photo 2 to Photo 16), many of which are parts of the UNESCO World Cultural Heritage sites in the Kathmandu Valley. A disproportionately high percentage of such structures collapsed during to the 2015 earthquake shaking, compared to the brick masonry and reinforced concrete frame buildings in their immediate neighborhood, most of which did not collapse and mostly suffered only minor visible damage.

Various possible explanations for the higher level of earthquake damage to the temples and the heritage structures are as follows:

- Age (the heritage structures are generally older than the surrounding buildings)
- Lack of maintenance
- Unusual structural systems (higher flexibility, larger masses)
- Pre-existing damage and cracks due to past strong earthquakes of 1833 and 1934
- Hasty and poor-quality reconstruction after collapse caused by the 1934 earthquake

The natural frequencies of these monumental structures usually differ significantly from those of normal brick masonry buildings. This could also have made them more vulnerable to the ground motion of the main shock dominated by long period motions.

It is interesting to note that some old temples that have survived the 2015 earthquake are also known to be those that suffered the least damage in the 1934 earthquake disaster, for example the Akash Bhairav Temple (Photo 17) at Indrachowk, Kathmandu, the Pashupatinath Temple in Kathmandu and the Nyatapole Temple (Photo 12) at the Taumadhi Square, Bhaktapur (Shakya, 2000). In the Nyatapole Temple, the highest pagoda temple in Nepal, only the uppermost storey shows externally visible damage, which seems to a re-run of the 1934 earthquake damage to this temple, as recalled by some elderly people in Bhaktapur. An investigation of the possible reasons (e.g. more robust structural system, better maintenance, etc.) for the apparent earthquake resilience of these temples could provide valuable hints for the earthquake-resistant redesign of the collapsed temples.

7.2 Earthquake damage to stone rubble masonry houses

In the mountainous regions of Nepal, a majority of people live in houses made of stone rubble masonry held together with mud mortar. Such structures are inherently vulnerable to sudden brittle failure when subjected to strong earthquake shaking (see Photo 19 and Photo 20).

In some mountainous regions of Nepal, almost 100% of such stone masonry buildings collapsed during the 2015 earthquake sequence. This is the main factor behind the high death toll in the mountainous Sindhupalchok district, where 3423 deaths were confirmed as of 17 May 2015, accounting for about 40% of the total number of 8567 people killed in the 2015 Nepal earthquake disaster. Also in other mountainous districts, such as Nuwakot, Dhading, Rasuwa, Gorkha, Kavrepalanchok, etc., many stone rubble masonry buildings failed, causing numerous injuries and deaths.

To minimize losses of lives and property in the rural area during inevitable future earthquakes, it is urgently necessary to spread the knowledge about cost-effective means to improve the earthquake resistance of stone masonry buildings. It would be a mistake if the collapsed buildings are hastily rebuilt without incorporating earthquake-resistant features.

Numerous landslides triggered by the earthquake have also proven to be deadly in the mountainous regions with unstable slopes. Hence, it is necessary to make detailed geological hazard surveys to identify zones particularly vulnerable to rockfalls and landslides. Such locations have to be officially declared as danger zones where building activities are no longer permitted.

7.3 Earthquake damage to brick masonry houses in Kathmandu Valley

A majority of buildings in the old towns and villages in the Kathmandu Valley are made of brick masonry held together by mud mortar. Such buildings are also vulnerable to earthquake damage, although somewhat less than the stone rubble masonry buildings. Many brick buildings also collapsed due to the ground shaking caused by the 2015 earthquake (see Photo 21 to Photo 29).

A great majority of such old brick buildings in the Kathmandu Valley (probably more than about 90%) surprisingly did not collapse during such a strong earthquake with a magnitude of 7.8 M_w. However, many have suffered various degrees of damage (see Photo 34 to Photo 37). Among the three largest old towns of Kathmandu, Patan and Bhaktapur, the percentage of collapsed brick buildings appears to be the highest in Bhaktapur. In some smaller towns and villages, such as Sankhu and Lubhu, the level of destruction of old brick buildings seems to be substantially higher.

The low collapse rate of the old brick masonry buildings has fortunately helped to keep the total number of casualties in the Kathmandu Valley substantially below the predictions of various earthquake risk assessments. For example, in connection with the Kathmandu Valley Earthquake Risk Management Project (KVERMP), a study was carried out during the years 1997-1999 to estimate the possible earthquake damage on the basis of the historical data of the 1934 earthquake and casualty figures from earthquake disasters in other comparable cities. The results of this study indicated that about 40,000 deaths and 95,000 injuries could occur in the Kathmandu Valley in the next major quake (Dixit et al., 2000).

One possible mitigating factor that explains the discrepancy between the predicted and actual casualty figures could be that the 2015 earthquake having a magnitude of 7.8 M_w, although very strong, was not yet the worst possible event in the seismo-tectonic setting of the Himalayan region. The recorded peak horizontal acceleration of about 0.2 g in Kathmandu was not very high. Another possible mitigating factor in the case of the Kathmandu Valley is the fact that a very strong earthquake produces predominantly long period shaking on the surface of the very thick soil layer. As a result, the horizontal earthquake shaking would not be significantly amplified in a typical traditional 4-storey building, whose fundamental natural period would be of the order of 0.4 s.

In the old towns in the Kathmandu Valley, most brick buildings are usually built in a continuous row without any gaps between them. In conventional earthquake engineering, it is recommended to avoid such a configuration to prevent damage by pounding between buildings during a strong earthquake. However, some people have noted that such rows of buildings appear to have a better earthquake survival rate than isolated buildings, since each building is stabilized by adjacent buildings. It needs to be clarified if such a seemingly paradoxical, mutually beneficial stabilizing effect between adjacent buildings is plausible, at least when the relatively moderate ground shaking dominated by long period horizontal shaking does not lead to any significant pounding damage.

7.4 Earthquake damage to reinforced concrete buildings

Concrete buildings are relatively new in Nepal and have been built mainly since the 1960s. Such a building consists typically of a reinforced concrete (RC) skeletal frame with brick infill walls. The performance of the RC frame buildings in the 2015 earthquake was not necessarily superior to that of well-constructed traditional brick masonry structures. Many people are surprised that quite a few of these modern-looking structures also collapsed during the earthquake shaking (see Photo 38 to Photo 43). Quite a few recently built apartment blocks and shopping malls also suffered heavy damage, leading in some cases to a total loss of substantial investments of the owners of these expensive structures (see Photo 44).

The reinforced concrete (RC) structures were built in Nepal in many cases without performing proper structural analysis and design by a qualified structural engineer. Even when a structural analysis was carried out, more often than not the earthquake load considered in the design was too low, usually not more than about 0.1 g. Poor concrete quality and deficient reinforcement detailing are further factors that make the reinforced concrete structures in Nepal vulnerable to earthquake damage.

While an RC skeletal frame efficiently supports the static vertical gravity forces, it is not suitable to resist the substantial horizontal shear forces occurring during a strong earthquake. Many building owners are not aware of this fact, due to which a vast majority of the reinforced concrete buildings in Nepal have been built without proper shear walls, which would ideally be in the form of adequately reinforced concrete walls. As a result, the horizontal shear forces due to an earthquake would be carried primarily by the brick infill walls. These infill walls are, however, usually quite slender, with a thickness of not more than about 23 cm (one brick length). In fact, most internal partition walls and sometimes even external walls are only 11 cm (one brick width) thick (for example, see Photo 48). Such infill walls are prone to shear failure during an earthquake, often resulting in tell-tale X-cracks, as could be seen in many infill walls after the earthquake of 25 April 2015 (see Photo 52).

7.5 Collapse of boundary walls: an often overlooked hazard

An eye-catching feature of the 2015 Nepal earthquake is a very large number of collapsed boundary walls (see Photo 53 and Photo 54). The danger posed by possible failure and overturning of boundary walls during an earthquake is an often overlooked hazard. The building owners in Nepal typically build quite high walls around their compounds for security reasons (see Photo 55). Such walls tend to be quite slender and are mostly built of unreinforced brick masonry for economic reasons.

The collapse of unreinforced boundary walls also causes injuries and even deaths during earthquakes. For example, the only victims in the Kathmandu Valley of a relatively moderate 6.9 M_w earthquake of 18 September 2011, whose epicenter was in faraway Sikkim in India, were 3 persons killed and 4 persons injured by the collapse of the compound wall of the British embassy (nepalnews.com, 2011). The victims were travelling along the road outside the embassy.

Collapse of high boundary walls most probably caused casualties also in the 2015 Nepal earthquake disaster, although this has not been specially reported by the media focused on more spectacular building collapses. The collapse of high walls also blocked vehicle traffic through some narrow alleys in the Kathmandu Valley for many days after the earthquake, causing serious hindrances to disaster relief activities.

There is clearly a need to enforce earthquake-resistant design and construction of boundary walls in areas prone to high seismic risk.

7.6 Were some areas more vulnerable than others?

The damage caused by the 2015 earthquake disaster was not uniform. While very few collapsed buildings can be seen in some parts of the city, elsewhere, such as Sitapaila, Gongabu and Kalanki, a significantly higher percentage of buildings collapsed, causing a large number of fatalities. Many of these areas are new settlements established only in the last few decades. It needs to be clarified whether these areas have poorer subsoil conditions or even soil susceptible to liquefaction due to buildup of dynamic pore water pressures during a strong earthquake. Another factor that could have played a role in the non-uniform damage is the possible variation of the spectral content of the ground motion on the surface of the thick soil layer covering the Kathmandu Valley, since the thickness of this soil layer is variable.

8 Summary and concluding remarks

In the aftermath of the 2015 earthquake disaster, the special seismo-tectonic setting of the Himalayan region has become better known even among the general public in Nepal. The most important aspects of the seismic hazard in this region are as follows:

a) A strong earthquake in this region is usually caused by a dip-slip movement on an almost horizontal thrust fault.

b) The rupture zone of a very strong earthquake can have a huge area of the order of 10,000 km^2 or more.

c) The epicenter may not be located at the center of the rupture zone.

d) At a given location in the affected area, the fault rupture zone is usually much closer than the epicenter.

e) The earthquake damage in the affected region does not necessarily decrease with an increasing epicentral distance. Hence, the widespread tendency in the media and even among the experts to try to correlate the earthquake damage with the epicentral distance is generally misleading in the case of a strong earthquake.

f) Only modern attenuation laws using the minimum distance from the causative fault as a parameter should be employed in an earthquake hazard analysis in the Himalayan region. It could be necessary to develop or refine a representative attenuation model suitable for this region.

Apparently, only few good records of the strong ground motion produced by the 2015 Nepal earthquake series exist. So far the only publicly available records are from a single USGS station located at Kanti Path in Kathmandu. These records indicate that the ground motion in the Kathmandu Valley during a very strong earthquake is dominated by low frequency oscillations having a period in the range of 4 s to 5 s. This would imply that very tall and very flexible structures in the Kathmandu Valley would be more susceptible to damage during a strong earthquake and should be designed and built accordingly.

There is an urgent need to install many more strong-motion seismographs in Nepal, so that realistic seismic loads can be specified in the national building code on the basis of actual earthquake records to ensure a safe earthquake resistant design of structures. Such strong-motion instruments are not very expensive nowadays, but they do need good care and regular maintenance if they are to function when the next major earthquake strikes.

There is a great deal of fear among the public that the 7.8 M_w earthquake could be just a foreshock of an even stronger event. Unfortunately, the science of earthquake prediction is not very reliable and it is impossible to accurately predict the next devastating earthquake in a given region. This could happen sometime soon, but it could also take many more decades or even centuries.

It is needless to say that the only rational protection against future earthquake catastrophes of possibly even larger magnitudes is to improve the safety of the buildings and other structures. Thus, it would not be wise to rebuild the collapsed and heavily-damaged structures hastily without properly designing, planning and incorporating features to ensure sufficient earthquake resistance. Even an existing building that has suffered only relatively minor visible damage during the 2015 earthquake series may still be inherently structurally deficient. Also such buildings need to be identified and retrofitted or rebuilt. Of course, this is easier said than done, as it could involve substantial financial investments that could be beyond the means of the average building owner.

The tasks of rebuilding and strengthening poorly-built structures should be taken up as soon as possible also in other regions of the country not affected by the present disaster, since the next powerful earthquake may very well strike elsewhere. For instance, since no major earthquake has occurred in west Nepal since 1505 AD, this region is considered by some to be a “seismic gap” (i.e. region with an active fault that has not ruptured for a long time, but is known to be capable of causing a large earthquake) with an enhanced earthquake risk, as indicated in Fig. 12.

Fig. 12 **Rupture zones of major historical earthquakes in the Himalayan region and suspected “seismic gap” extending across west Nepal and eastern part of Uttarakhand state of India; rupture zone geometries are approximations based on Pandey and Molnar (1988), Avouac et al. (2001), Chamlagain (2009) and Shen-Tu (2015) (base map prepared with NCEI Natural Hazards Viewer; rupture zones were added by the author; dashed black ellipses: rupture zones of historical earthquakes prior to 1900; dashed red rectangles: rupture zones of earthquakes since 1900; dashed blue line with arrows: suspected "seismic gap")**

9 References

Avouac, J.P., Bollinger, L., Lavé, J., Cattin, R. and Flouzat, M. (2001). Le cycle sismique en Himalaya. C. R. Acad. Sc., Sciences de la Terre et des planètes / Earth and Planetary Sciences, Vol. 333, pp. 513–529.

Bilham, R. (2004). Earthquakes in India and the Himalaya: Tectonics, Geodesy and History. Annals of Geophysics, Vol. 47, No. 2/3, pp. 839-858.

CESMD (2015). Earthquakes Recorded by Station KATNP. Center for Engineering Strong Motion Data.
(see http://www.strongmotioncenter.org/cgi-bin/CESMD/StaEvent.pl?stacode=NPKATNP)

Chamlagain, D. (2009). Earthquake Scenario and Recent Efforts toward Earthquake Risk Reduction in Nepal. Journal of South Asia Disaster Studies, Vol. 2, No. 1, pp. 57-80.

Dixit, A.M., Dwelley-Samant, L.R., Nakarmi, M., Pradhanang, S.B. and Tucker, B.E. (2000). The Kathmandu Valley Earthquake Risk Management Project: An Evaluation. Proceedings of the 12th World Conference on Earthquake Engineering (12WCEE), Auckland, New Zealand, Jan. 31-Feb. 4, 2000.

Gahalaut, V.K. (2009). Earthquakes in India: Hazards, Genesis and Mitigation Measures. In Natural and Anthropogenic Disasters: Vulnerability, Preparedness and Mitigation, M.K. Jha (editor), Springer, Netherlands, pp.17-43.

Kumar, S., Wesnousky, S.G., Rockwell, T.K., Briggs, R.W., Thakur, V.C. and Jayangonda-perumal, R. (2006). Paleoseismic Evidence of Great Surface-Rupture Earthquakes along the Indian Himalaya. Journal of Geophysical Research (Solid Earth), Vol. 111, No. B3, B03304, doi:10.1029/2004JB003309.

Lavé, J. and Avouac, J.P. (2000). Active Folding of Fluvial Terraces across the Siwaliks Hills, Himalayas of Central Nepal. Journal of Geophysical Research, Vol. 105, No. B3, pp. 5735–5770.

Malhotra, P. (2015). Personal e-mail communication on 1 June 2015 with Praveen Malhotra of StrongMotions Inc., 110 Upland Rd, Sharon, MA 02067, USA.

McKinney, S.C. (2015). Caltech, JPL Team Captures Movement on Nepal Earthquake Fault Rupture. Latest News, Caltech, 15 May 2015.
(see http://www.caltech.edu/news/caltech-jpl-team-captures-movement-nepal-earthquake-fault-rupture-46709)

NCEI (2015). Global Significant Earthquake Database, 2150 BC to Present. National Centers for Environmental Information (formerly National Geophysical Data Center or NGDC), National Oceanic and Atmospheric Administration (NOAA), USA.

nepalnews.com (2011). Three victims of British Embassy wall collapse cremated.
(see http://www.nepalnews.com/archive/2011/sep/sep22/news02.php)

Newar, N. (2004). 70 Years After. Nepali Times, Issue 178.
(see http://nepalitimes.com/news.php?id=5065)

Oskin, B. (2015). Bigger Earthquake Coming on Nepal's Terrifying Faults. Article by Becky Oskin of Livescience.com, 28 April 2015.
(see http://www.cbsnews.com/news/bigger-earthquake-coming-on-nepals-terrifying-faults)

Pandey, M.R. and Molnar, P. (1988). The Distribution of Intensity in the Bihar-Nepal Earthquake of 15 January 1934 and Bounds of the Extent of the Rupture. Journal of Nepal Geological Society, Vol. 5, No. 1, pp. 22-44.

Rajendran, C.P., Rajendran, K., Sanwal, J. and Sandiford, M. (2013). Archeological and Historical Database on the Medieval Earthquakes of the Central Himalaya: Ambiguities And Inferences. Seismological Research Letters, Vol. 84, pp. 1098-1108.

Rao, N.P., Kumar, P., Kalpna, Tsukuda, T. and Ramesh, D.S. (2006). The Devastating Muzaffarabad Earthquake of 8 October 2005: New Insights into Himalayan Seismicity and Tectonics. Gondwana Research, Vol. 9, pp. 365-378.

Seed, H.B. and Idriss, I.M. (1970). Soil Moduli and Damping Factors for Dynamic Response Analysis. Report No. EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley, USA.

Shakya, N.M. (2000). Temples and Buildings Standing over Kathmandu Valley which are Vulnerable to Earthquakes. Earthquake-Safe: Lessons to Be Learned from Traditional Construction, International Conference on the Seismic Performance of Traditional Buildings, Nov.16-18, 2000, Istanbul, Turkey.
(see http://www.icomos.org/iiwc/seismic/Shakya.pdf)

Shen-Tu, B. (2015). Did the Nepal Earthquake Close the Gap? In Focus, The AIR blog about risk, modeling, and industry buzz, 4 May 2015.
(see http://www.air-worldwide.com/Blog/Did-the-Nepal-Earthquake-Close-the-Gap-)

Srivastava, H.N., Bansal, B.K. and Verma, M. (2013). Largest Earthquake in Himalaya: An appraisal. Journal of the Geological Society of India, Vol. 82, No.1, pp. 15-22.

USGS (2015a). The April-May 2015 Nepal Earthquake Sequence, The April 25, 2015 M 7.8 Gorkha Earthquake and its Aftershocks, including the May 12, 2015 M 7.3 Event, Earthquake Educational Slides. Created & Compiled by Gavin Hayes, U.S. Geological Survey, National Earthquake Information Center (version downloaded on 27 May 2015).
(see http://earthquake.usgs.gov/learn/topics/Nepal_Slides.pdf)

USGS (2015b). Technical Appendix: USGS Numerical Aftershock Analysis for the Magnitude 7.8 Gorkha earthquake in Nepal April 25, 2015 (as of May 27, 2015). U.S. Geological Survey.
(see http://earthquake.usgs.gov/earthquakes/eventproducts/us20002926/aftershock-statistics.pdf)

Vucetic, M. and Dobry, R. (1991). Effect of Soil Plasticity on Cyclic Response. Journal of Geotechnical Engineering, ASCE, Vol. 117, No. 1, pp. 89-107.

Appendix

Photo documentation of effects of 7.8 M_w earthquake of 25 April 2015

This photo documentation consists of a selection of photos taken from 27 April to 1 May 2015 by the author, who was in Chitwan at the time of the earthquake of 25 April 2015. Most of the photos show the effects of the earthquake of 25 April 2015 on the structures in the cities of Kathmandu, Lalitpur (Patan) and Bhaktapur in the Kathmandu Valley. A few photos were taken during the author's travel back to Kathmandu along the Tribhuvan Highway on 27 April 2015.

As all the photos were taken before the strong aftershock of 12 May 2015, they would not show any possible additional damage caused by this later event.

Photo 1 Rockfall practically blocking Tribhuvan Highway near Sim Bhanjhang on 27 April 2015

Before earthquake
(Photo: Manoguru / Wikimedia Commons)

After earthquake
(Photo: Sujan Malla)

Photo 2 Kalmochan Temple on the bank of Bagmati river at Tripureshwor, Kathmandu before and after the 25 April 2015 earthquake

Before earthquake
(Photo: Sugat Shrestha / Wikimedia Commons)

After earthquake
(Photo: Sujan Malla)

Photo 3 Dharahara tower in Kathmandu before and after the 25 April 2015 earthquake

Before earthquake (Photo: Ganesh Paudel / Wikimedia Commons)

After earthquake (Photo: Sujan Malla)

Photo 4 Kasthamandap Temple in Kathmandu before and after the 25 April 2015 earthquake

Photo 5 **Pagoda temple whose detached upper storey landed several meters away at Kathmandu Durbar Square**

Before earthquake
(Photo: Bgabel / Wikimedia Commons)

After earthquake
(Photo: Sujan Malla)

Photo 6 **Trailokya Mohan Narayan Temple at Kathmandu Durbar Square before and after the 25 April 2015 earthquake**

Photo 7 Structural damages to palace complex, Kathmandu Durbar Square

Photo 8 Collapsed buildings on Swayambhu hill

Photo 9 Earthquake destruction of a shikhara temple beside Swayambhunath Stupa

Photo 10 Patan Durbar Square after the 25 April 2015 earthquake

Before earthquake

After earthquake

Photo 11 Bhaktapur Durbar Square before and after the 25 April 2015 earthquake (the elegant Vatsala temple collapsed during the earthquake)

Photo 12 Nyatapola Temple at Taumadhi Square, Bhaktapur with damage in the uppermost level

Photo 13 Bhairavnath Temple at Taumadhi Square, Bhaktapur with significant damage in the uppermost level

Photo 14 Temples with substantial damage in Kathmandu

Photo 15 Temples in Kathmandu with significant cracks

Photo 16 Pujari Math in Bhaktapur with partial wall collapse

Photo 17 Akash Bhairav temple at Indrachowk, Kathmandu with no externally visible damage

Photo 18 Dattatreya temple in Bhaktapur with no externally visible damage

Photo 19 Stone rubble masonry building with end wall collapse along Tribhuvan highway

Photo 20 Partially collapsed stone rubble masonry buildings along Tribhuvan highway

Photo 21 Brick masonry building with end wall collapse in Kathmandu

Photo 22 Partially collapsed brick masonry building in Kathmandu

Photo 23 Collapsed brick masonry building in Kathmandu

Photo 24 Collapsed brick masonry building in Kathmandu

Photo 25 Collapsed brick masonry buildings in Bhaktapur

Photo 26 Brick masonry buildings with collapsed upper storeys in Bhaktapur

Photo 27 Collapsed gable wall at the south end of Durbar High School in Kathmandu

Photo 28 Collapsed gable wall of a brick masonry building at Jamal in Kathmandu

Photo 29 Narrow alleys blocked by collapsed buildings in Bhaktapur

Photo 30 Narrow alley blocked by collapsed brick structures in Kathmandu

Photo 31 Hazard posed by dropping bricks in a narrow alley in Kathmandu

Photo 32 **Rows of old brick masonry buildings near Indrachowk that survived the earthquake with only minor visible damages**

Photo 33 **Main street at Pako near New Road in Kathmandu with no visible building damage after 25 April 2015 earthquake**

Photo 34 Brick masonry buildings with major cracks caused by earthquake shaking

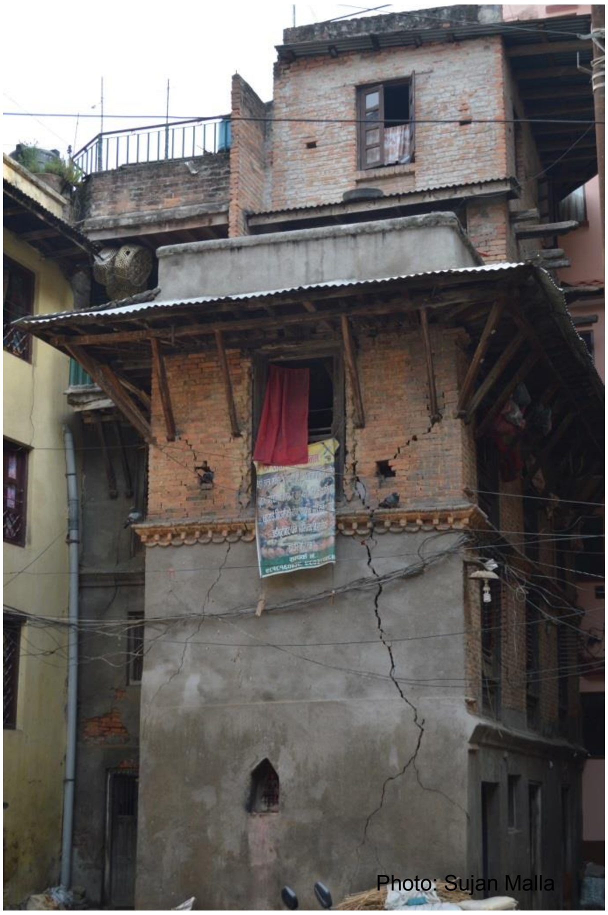

Photo 35 Brick masonry buildings in Kathmandu with major cracks caused by earthquake shaking

Photo 36 Brick masonry building in Bhaktapur with major cracks

Photo 37 A building of National Museum at Chhauni, Kathmandu with severe cracks

Photo 38 Soft-storey failure of a reinforced concrete frame building at Paropakar Marg, Kathmandu

Photo 39 Soft-storey failure of a reinforced concrete frame structure at Sitapaila in Kathmandu

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Photo 41 Collapsed reinforced concrete building at Tripureswor in Kathmandu (front and side views)

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Photo 44 CTC Mall, Sundhara, Kathmandu with substantial earthquake damage

Photo 45 Seriously damaged building with complicated geometrical features

Photo 46 Office building which is no longer useable due to significant damage

Photo 47 Significantly damaged building of Acme Engineering College, Sitapaila, Kathmandu

Photo 48 Heavily damaged building at Sitapaila, Kathmandu with brick infill walls of about 11 cm (half brick) thickness

Photo 49 Residential buildings with significant cracks at Sitapaila, Kathmandu

Photo 50 Building with a tilt due to earthquake damage

Photo 51 Multi-storeyed apartment block at Sitapaila, Kathmandu with substantial damage

Photo 52 X-cracks in masonry infill walls of RC frame buildings

Photo 53 Boundary wall collapse blocking a sidewalk

Photo 54 Collapsed boundary wall blocking a narrow access road in Kathmandu

Photo 55 Very high boundary wall with significant earthquake-induced cracks in Kathmandu

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