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Salient Aspects of the 2015 Mw 7.8 Gorkha Nepal Earthquake in Central Himalaya

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Abstract

Seismological parameters are compiled for the Mw 7.8 April 25, 2015 Gorkha earthquake that occurred 80 km NW of Kathmandu in central Nepal. The salient aspects of tectonics, slip, geodetic deformation, aftershocks and damage caused are also highlighted. As there were networks of seismographs, accelerographs and GPS stations over the rupture zone and there is availability of InSAR as well as teleseismic broadband seismograph data, some workers could study details of rupture process that has given new insights about strong ground motion generation. A major aftershock of Mw7.3 was stress-triggered on May 12, 2015. There were three aftershocks of Mw 6.5 to 6.7 and over 350 of M≥4 until August 2015. Rupture zone is 150kmx55km and rupture duration is 80 s making an overall very low rupture propagation velocity of 2 km/s. However, major portion of the rupture propagated at normal velocity of 3 km/s. The April 25 main shock is located at the NW end of the rupture zone and the May 12 earthquake at its NE end. Rupture propagated eastward. Slow built up of the seismic moment rate has generated less high frequency acceleration (pga) while the long tail of seismic moment rate has generated strong acceleration in period range 3-6 s. Lower pga 0.19g has caused restricted damage to low-rise buildings. The short-period acceleration around 0.5 -1.0s period has caused toppling of ~ 27m tall Dharahara tower. As there were no tall structures the large acceleration for long periods has been of not much consequence to Nepal. However, it has caused World-wide worry for tall structures in active zones. The rupture has been restricted up to Main Boundary fault and has not come south up to Main Himalayan Front as happened during 1934 M8.4 earthquake. Due to this reason and low pga the damage in India is limited.

Keywords: Nepal earthquake, rupture process, damage to heritage structures, damage due to earthquakes

1. Seismological parameters of the main shock and largest aftershock

The April 25, 2015 (06:11 UT) earthquake of M_w 7.8, epicenter 28.230˚N 84.731˚E, depth 8.2 km (USGS), at Gorkha, central Nepal occurred 80km northwest of Kathmandu (Figs. 1 2, and 3). The earthquake was followed by number of aftershocks and the largest among them of M_w7.3 was triggered~150km east of the main shock on May 12, 2015 at 27.809˚N 86.17˚E, depth15km.The epicenter of the main shock is located in the Lesser Himalaya to the south of Main Central Thrust (MCT). However, a major part of the rupture zone and epicenter of the May 2015 largest aftershock fall in the Higher Himalaya, north of MCT (Figs. 2 & 3). Kathmandu is in between the epicenters of April and May earthquakes. Rupture area of the main shock is 150 km x 55 km as indicated by the aftershocks, GPS, InSAR measurements and slip modeling. It is interesting to note that the main shock occurred at the NW end of the rupture zone near Gorkha, while the largest aftershock occurred at the NE end of the rupture zone close to Dolakha-Sindhupalchowk-Kodari area (Fig.3). Rupture of the main shock propagated eastward and continued further eastward by the May 12 largest aftershock. Rupture zone of the May 12 earthquake is about 50km wide as indicated by its aftershocks. The aftershocks of the May 12 event occurred between the rupture zones of the April 2015 and January 1934 earthquakes.

Rupture areas of the April and May 2015 main earthquakes are based on aftershock distribution and 3D rupture modeling by various workers. Rupture area of the 1934 earthquake is based on the fault length 180km estimated from the relation magnitude vs. length, $\log(L) = 0.62M = 2.16$ of Press (BSSA, 1967), where fault length, L is in cm. Width is taken as 110km that is distance between the epicenters estimated by Pandey and Molnar (1989) shown in Fig.3 and that by USGS towards the northern end of the rupture zone (refer fig. 5) which define the severely affected area.

The Nepal Himalaya has experienced repeated destructive earthquakes in the past that affected Kathmandu with MM intensity X in 1255, 1344, 1408, 1681, 1833 and 1934.The 2015 Nepal earthquake (MM intensity IX) was as a result of the rupture of a part of the locked Main Himalayan Thrust (MHT), the detachment plane, along which the Himalayan wedge thrusts over the Indian plate with a convergence rate 17-21mm/y (Ader et al., 2012). All the past great/large earthquakes are believed to have occurred on the MHT with thrust faulting.

The focal mechanisms suggest that both the 2015 main shock and large aftershocks occurred due to thrusting on a WNW-ESE trending north-dipping shallow (5^o-7^o) thrust fault (Galetzka et al., 2015). The main shock rupture propagated eastward at a velocity of 3km/s for large part of the duration of rupture of April 25 near Kathmandu but at lesser speed in the beginning and at the end of rupture. Duration estimated by IRIS (Fig. 4) is about 60s with peak moment release between 25s and 40s. A large energy is released 20s after the start, and as the rupture propagated eastward the large slip has occurred about 60 km east of the epicenter and near Kathmandu. Galetzka et al. (2015) and Avouac et al. (2015), however, estimated slightly larger rupture duration of 70 s and 80 s, respectively.

2. Geodetic deformation

For the first time rupture of a major earthquake happened to occur beneath a dense high-rate continuous GPS network. The data of GPS stations, InSAR, strong motion accelerographs and teleseismic seismographs is used by researchers to model the kinematics of source process of the 2015 large event. Galetzka et al. (2015) modeled a slip pulse of ~20km width, ~6 s duration, and with a sliding velocity of 1.1 m/s. From the smooth onset of source-time function, they infer large ~5 m slip-weakening distance which indicates lower friction that caused moderate ground shaking (~16% g) at high frequencies (>1 Hz) and limited damage to regular dwellings. One of the two GPS stations on the inferred rupture plane showed maximum 2m southward co-seismic movement with a rise time of 6 s. Post-seismic deformation is, however, negligible.

Figure 1. **Geographical map of Nepal**

The deformation model from teleseismic waveforms for the main shock of April 25, 2015 (Mw 7.8) is illustrated in Fig 5a (Polet, website). It shows that the April, 2015 earthquake resulted up to 6.5m slip towards south in an area beneath and around the Kathmandu valley; maximum slip occurred near Kathmandu. A USGS report shows slip maps for the earthquakes of April 25 and May 12, 2015 (Mw 7.3) earthquakes as well as rupture zone of the January 1934 (Mw 8.4) earthquake (Fig 5b).

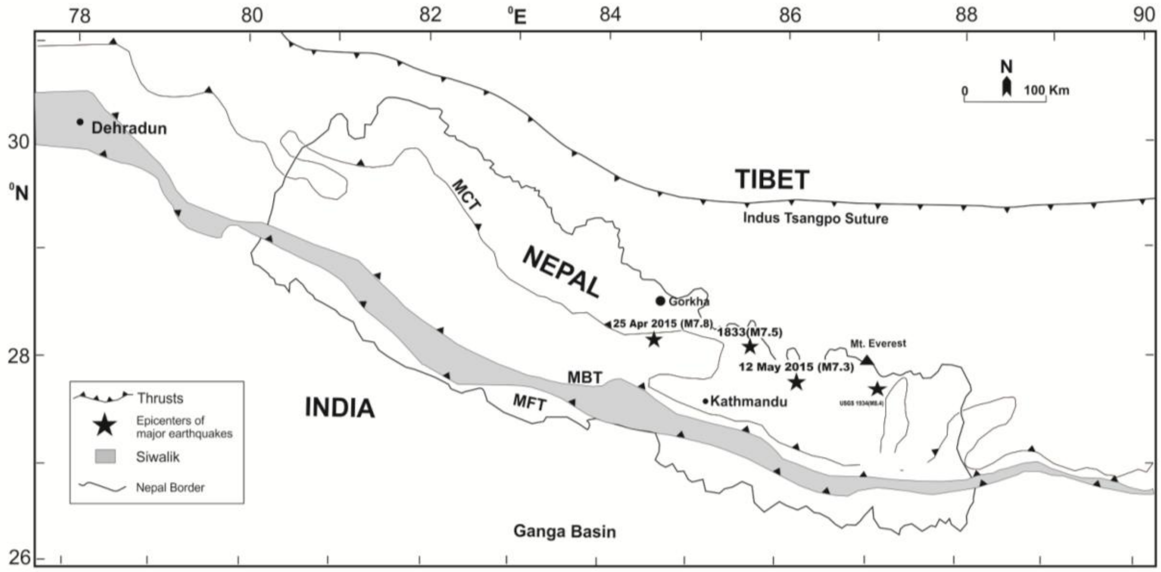


Figure 2. **Major thrusts and epicenters of the major earthquakes of Nepal since 1833.**

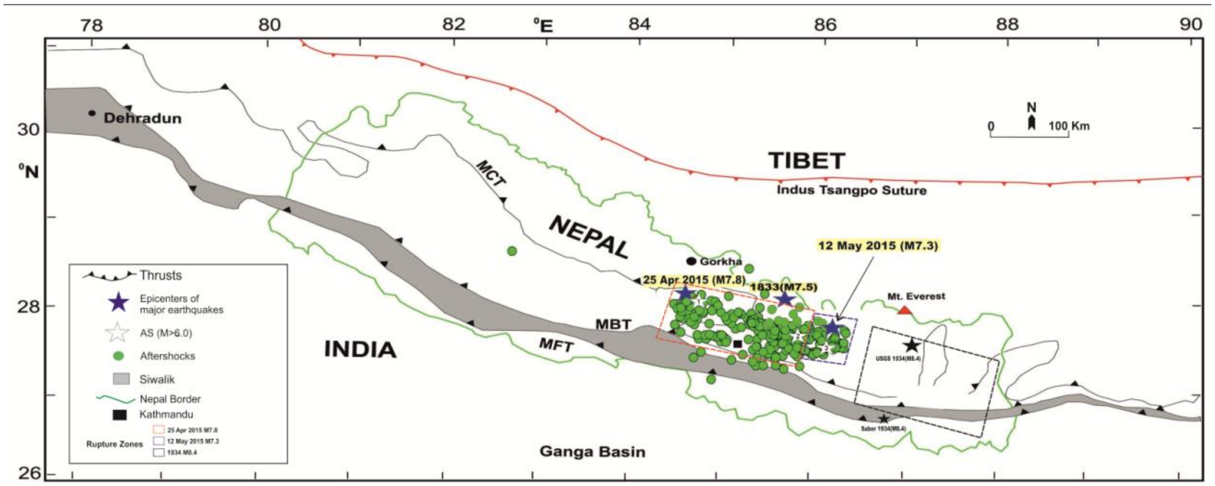
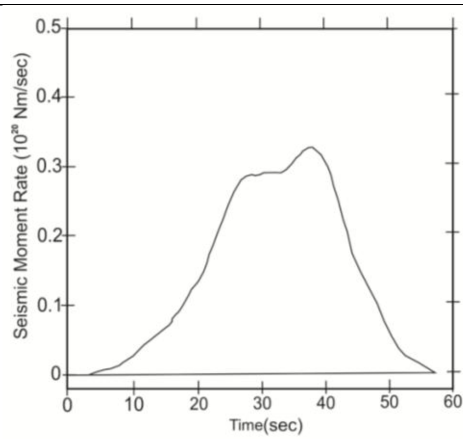


Figure 3. **Possible rupture zones of the 1934 great earthquake (Mw 8.2), the April 2015 (Mw 7.8) earthquake and May 2015 (Mw 7.3) earthquake. Longitude 86.1^{0}E is roughly the boundary between aftershocks of April 25 and May 2015 earthquakes. Aftershocks are taken till August 2015. It is to be noted that the 2015 rupture plane is not overlapping with the 1934 rupture plane.**

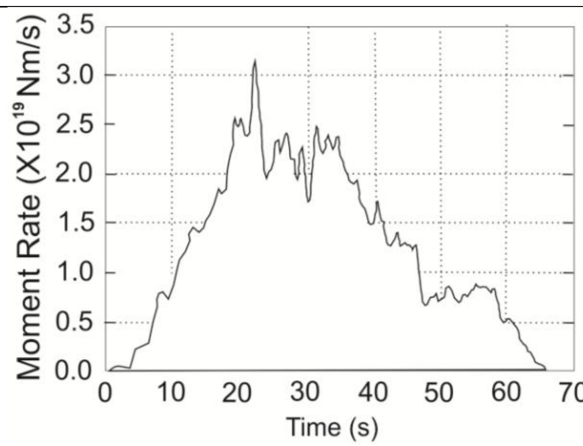
The InSAR data show an uplift of a land by 1 m (Polet, website) whereas part of southern Tibet in the north shows subsidence. The Mt. Everest, located about 200km ENE of Kathmandu, subsided by 2.5 cm. It has been suggested that the rupture has initiated at the locked part of the MHT at a depth ~10 km near Nepal-Tibet border; it propagated southward along the MHT and ended at some depth north of the Main Boundary Thrust (MBT). The rupture did not break the surface.

3. Damage and MM intensity

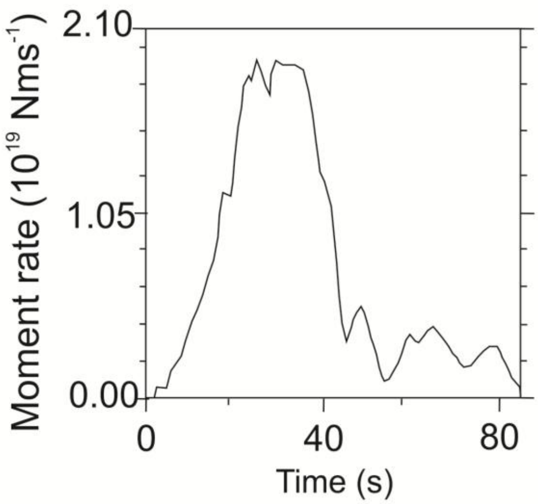
The main shock and May 12 aftershock caused 9000 human deaths, 17, 866 injured, 500, 717 collapsed houses and 269,190 severely damaged. Some 79 people died in India, mostly in Bihar and UP but stray incidences in West Bengal, Jharkhand and Odisha. A total of 25 people died in China. Collapse of a number of heritage structures is an irreparable loss. The economic loss is more than US$ 5 billion and reconstruction cost is estimated to be $20 billion. Modified Mercalli (MM) intensity IX is assigned to an area75kmx15 km, east-west trending zone, through Kathmandu where RC structures have collapsed. The intensity VIII covers rest of the rupture zone. Intensity VII extends up to Indian border region. In northwestern Bihar and adjoining UP, up to 170km from the epicenter, some houses have collapsed. Here intensity VI is assigned as only some shabby constructions have collapsed. One building collapsed in Siliguri at 300 km distance. Earthquake has been strongly felt up to Delhi with intensity IV while intensity III extends to 1500 km distance in Gujarat (like in Ahmedabad) in the west, in Odisha and West Bengal (like in Kolkata) in the east and some parts in Andhra to the southeast from the epicenter. Numerous landslides of different nature like Valley Blocking, extensive ones and many more of limited widths have occurred throughout the rupture zone. Rock falls had blocked several roads. Some ice-rock avalanches occurred at elevations 3500m and above.



(a)

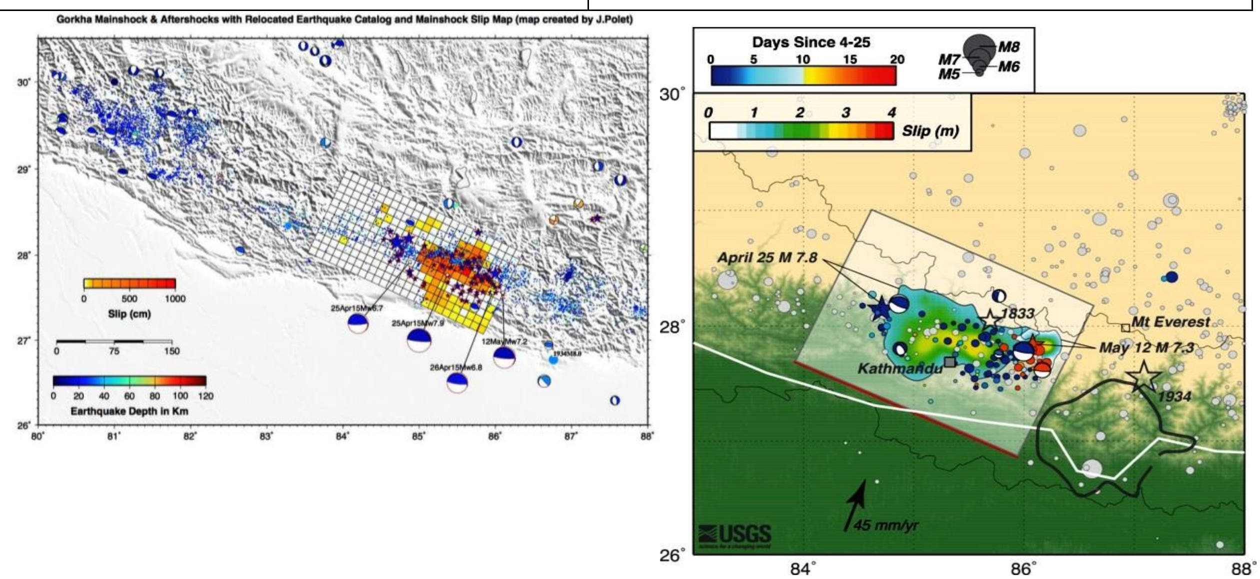


(b)



(c)

Figure 4. Seismic moment rate for the Nepal earthquake of April 25, 2015 (orthogonal to fault strike) indicates (a) rupture duration of a minute (after IRIS/Michigan). Best-fit focal depth = 13km, seismic moment for 57 sec duration = $8x10^{20}$ Nm (Mw = 7.9), Moment Tensor Principal Axes P, N and T (units of10^{20} Nm): Value, Plunge, Azm = -8.1, 0.2, 7.9; 39, 2, 51; 193, 101, 8. Focal Mechanism: Strike, Dip and Rake = 299, 7, 108; 100, 84, 88. (b) rupture duration 65 s by Galetzka et al. (c) 80 s by Avouac et al.



(a) (b)

Figure 5. (a) Slip map of the April 25, 2015 earthquake, and its aftershock epicenters (after Polet, website) prior to the occurrence of May 12 earthquake. It shows up to 6.5m slip north of Kathmandu, but no slip at the site where May 12 earthquake occurred (b) Slip map for the April 25 and May 12, 2015 major earthquakes and the rupture zone of the January 1934 great earthquake. It shows 1 m slip for May 12 earthquake (USGS Report).

The 12th May earthquake caused landslides and collapse of several hundred houses and buildings including some RC structures in Dolakha-Sindhupalchowk-Kodari area. The death toll due to this earthquake was about 1000 in Nepal.

4. Aftershocks

The Mw 7.8 April 25, 2015 main shock occurred near Gorkha at the northwestern end of the150kmx55km rupture zone. It had two large aftershocks within hours: one Mw 6.6 occurred within half an hour, close to the main shock and the other of Mw 6.7 occurred 25 hours after the main shock some 130km ENE of the mainshock. Aftershocks of Mw >4 have continued for months in the entire rupture zone. The May 12, Mw 7.3 largest aftershock occurred at the northeastern end of the rupture zone near Dolakha, Kodari and Sindhupalchowk. As is evident from its aftershock sequence, it has ruptured a new area in between the rupture zones of the April 2015 and January 1934 (Mw 8.2) earthquakes. It is interesting to note that the April 2015 as well as the May 2015 large earthquakes occurred close to the northern edge of the locked zone and just south of the snow-peaked high Himalayan hills. The aftershock / rupture zone is mostly confined to the Higher Himalaya in north of MCT (Fig 3). The April earthquake had over 225 aftershocks of Mw≥4.0 and the May earthquake had about 125 aftershocks till August 2015. Aftershocks spread over the rupture zones of the two major earthquakes.

5. Strong motion

An accelerograph at Kathmandu maintained by Directorate of Geology & Mining of Nepal recorded PGA of 16.4% g for the April earthquake. The data are also available from a NetFlixmems accelerometer installed by the USGS in the US Embassy in Kathmandu which shows pga 19% g. The recorded PGA of 16-19% g is relatively mild as compared to its magnitude. The USGS preliminary estimation of the expected maximum ground acceleration (PGA) was about 0.35g. The 1934 Nepal Mw 8.2 earthquake, at a distance of 150 km caused destruction of 20% buildings in Kathmandu as compared to <1% by the 2015 earthquake. Decay of acceleration with distance for the April 2015 Gorkha earthquake is also much faster. Acceleration, converted velocity and displacement spectra are depicted in Fig. 6.

It may be noted that the recorded PGA may be 2-3 times amplified value of the generated motion in hard rock. The strong motion is dominated by low-frequency (3 to 6 seconds) ground shaking. Spectral acceleration of up to 60%g is estimated for natural periods of 0.1-0.5 which may be corresponding to 1-5 storey buildings and for periods of 3-6 sec which may be corresponding to tall structures of 30-60 storeys. Since the horizontal base yield strength of most tall buildings is less than 15%, we can expect that 19% PGA will cause yielding in tall buildings. The PGV of 107 cm/s and PGD of 139cm indicate very strong shaking for long-period structures. This level of long-period motion may cause collapse of most (or all) of the world's tall buildings. One of the GPS station has shown strong oscillations of 3-4 s period for 20s (besides high frequency oscillations) giving surface velocity of 70cm/s.

The earthquake was on a thrust fault with several meters of slip directly beneath Kathmandu that moved the city by meters in response. Rupture process of a major earthquake with 150km fault length will cause generation of low frequencies. The generated low frequency ground motion may also be mild as the recorded one will be the amplified one.

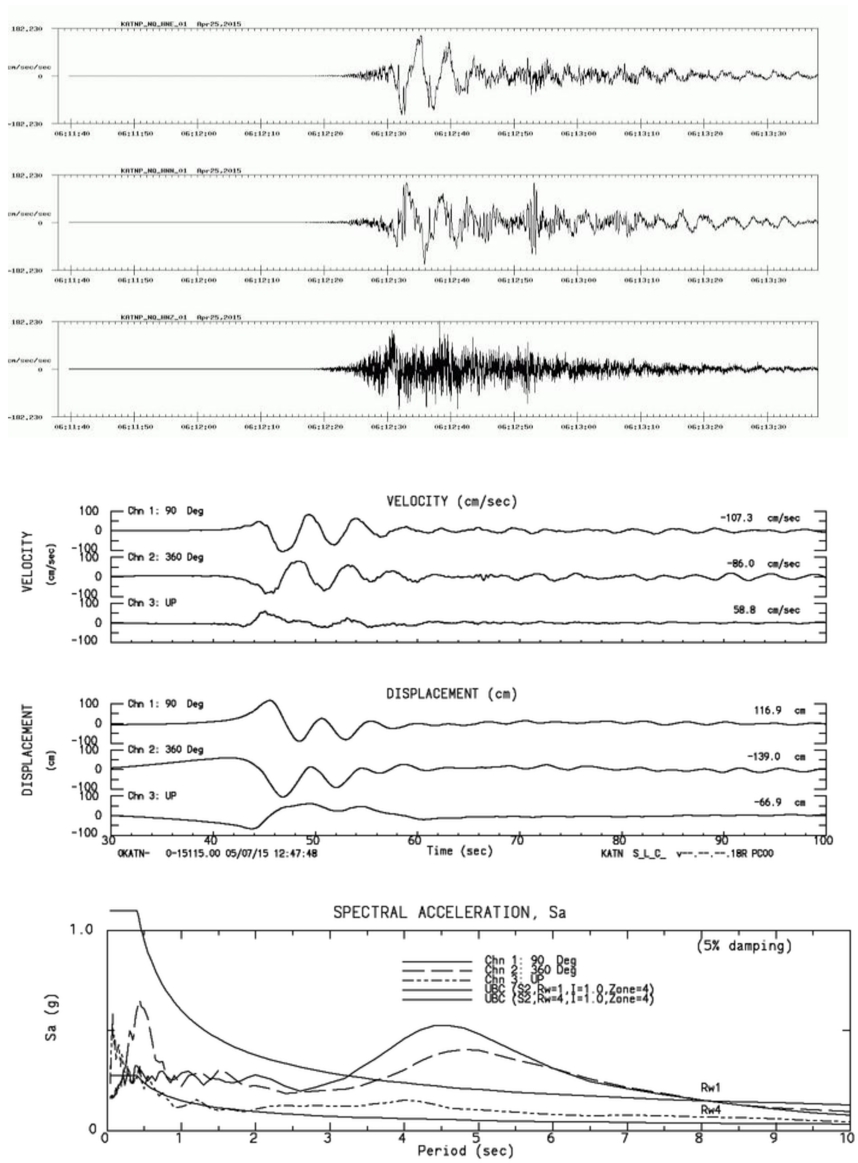


Figure 6. **Max. Acceleration ~ 186 cm/s² for bottom trace(V), 158 and 164 cm/s² two H), ground velocity (~107 cm/s), displacement (139 cm) and spectral acceleration (max 600 cm/s² at 0.1s in vertical component and 700 cm/s² at 0.5s in horizontal component) at Kantipath, Kathmandu (epicentral distance 60km) for 2015 Nepal earthquake. Large strong motion at higher periods is called 'Fling effect" which is caused by propagation of rupture over the rupture zone that causes heavy damage. It is seen at Kathmandu station by the large phase after the P-arrival.**

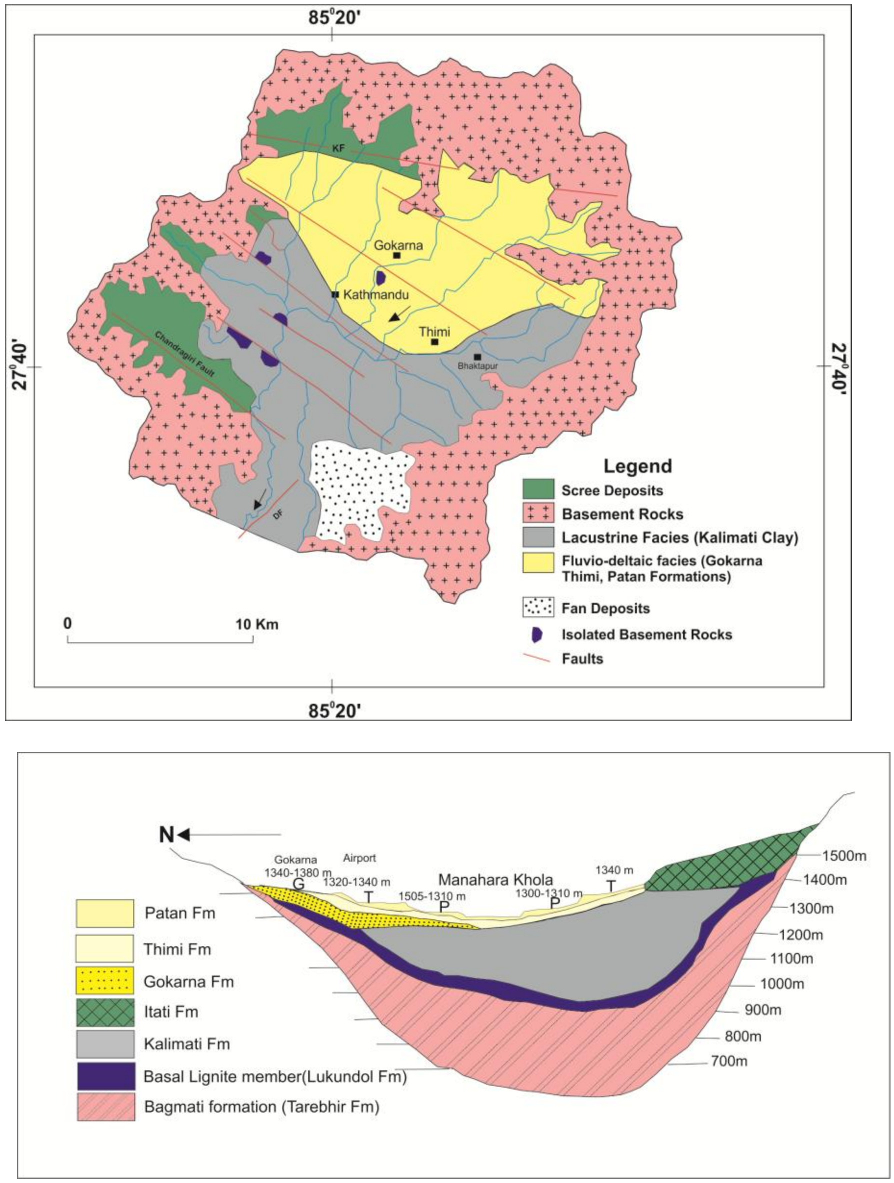


Figure 7. (a) Geological map of the Kathmandu valley, (b) schematic geological cross-section along N-S (after Sakai, 2001)

The high frequency amplification is caused by near-surface soil layers while the low-frequency (period 3 to 6 seconds) ground amplification is caused by 250-650 m deep Kathmandu basin of soft sediments. Resonance frequencies due to sedimentary layers at 250 to 650 m depths (Fig. 7) with shear wave velocity (Vs) of 300 to 400 m/s would be in the range of 3-6 sec (or f = 0.3-0.17Hz) based on the relation: H=Vs/4f. This would cause increased duration and amplification of shaking in long-period range. The spectral acceleration, Sa of up to 0.25g in long-period range might have caused large velocity and displacements which might have caused collapse of high-rise structures. There were no tall structures. The heritage structures are less than 4 storeys. Such structures are damaged by natural periods 0.1 to 0.5 s (Frequencies 10 to 2 Hz). Such resonance is caused by soil layers in depth range 5-25m with Vs 200 m/s.

The attenuation of strong motion together with observed and inferred data from the collapsed or toppled structures are shown in Fig. 8. The data are roughly consistent with available empirical relations proposed by various researchers.

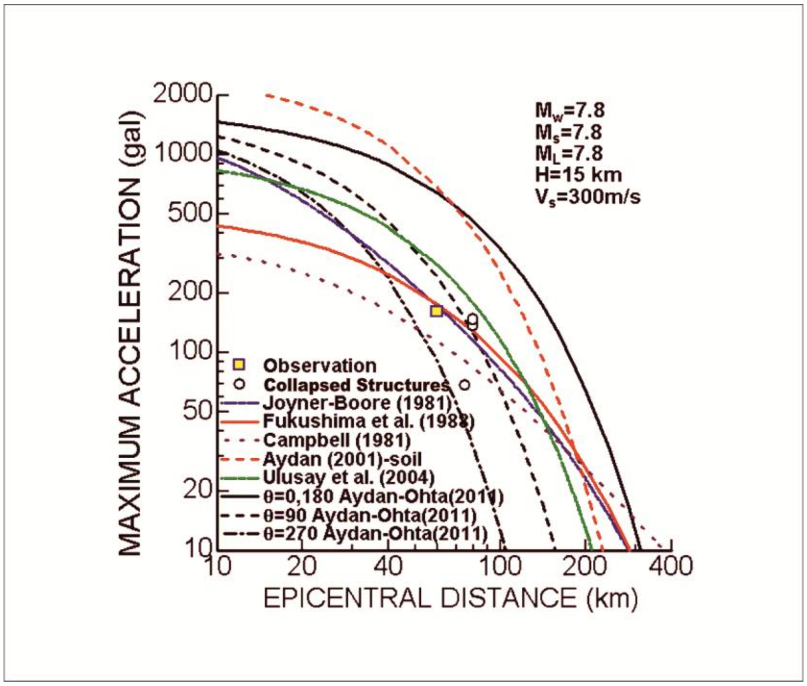


Figure 8. **Comparison of various empirical relations for attenuation of maximum ground acceleration, observed and inferred (Aydan and Ulusay, 2015).**

6. Conclusions

The April 25, 2015 earthquake of Mw 7.8 and its major Mw 7.3 aftershock of May 12, 2015 have caused 9000 human deaths and collapse or severe damage of 800,000 houses. The fault has not broken the surface. The PGA of 16-19% g is mild and structural damage is somewhat subdued. An important observation is that the strong motion at long periods 3-6 s is amplified over the deeper basins; the tall structures need to be designed accordingly in active areas. Rupture of the 2015 Gorkha earthquake started near Nepal-Tibet boundary and stopped 50km short of the Himalayan front. This is in contrast to the 1934 earthquake the rupture of which propagated to the Himalayan front causing destruction in India too.

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