

# THE GORKHA EARTHQUAKE AND THE TEHRI DAM

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## ABSTRACT

The Tehri dam was designed to withstand a  $M_w=7.2$  earthquake resulting in 0.25 g of shaking for 20 seconds. Geophysical advances in understanding earthquake genesis in the Himalaya have revised upward the maximum credible earthquake for the dam from  $M_w=7.2$  to  $M_w=8.5$ , with conjectural peak accelerations possibly exceeding 1 g, and with much prolonged shaking duration. Strong motion data from the 2015 Gorkha earthquake suggest that the Tehri dam could readily survive a replica of the  $M_w=7.8$  earthquake should one occur in the Garhwal Himalaya. The possibility of scaling the Gorkha strong motion record to emulate a possible  $M_w=8.5$  earthquake is introduced in the context of macroseismic intensities observed in the 1934 and 2015 earthquakes. A doubling in the amplitude of the slip pulse between these two earthquakes is probably associated with a doubling in acceleration, although this was not confirmed from intensities observed above points where surface slip doubling occurred in the Gorkha earthquake.

## I. INTRODUCTION

The Tehri dam is an earth-fill dam with the approximate shape of a tetrahedron. Its 1.1-km-long lower edge follows one of the two rivers it now impounds, and its 0.57-km-wide crest straddles the gorge through which the Bhagirathi River once flowed. The dam rises 260.5 m above the valley floor and its reservoir can store 4 km<sup>3</sup> of water in a 30-km-long approximately east-west sinuous valley with a surface area of 52 km<sup>2</sup>. It was completed in 2006 at a cost of \$1000M and provides a power generation capacity of 1 GW. The dam is without doubt a remarkable engineering achievement (Adikhari, 2009) and although it is among the sixth highest in the world, it is less than half the 650 m crest height of the Usoi dam that was created in less than 2 minutes by an earthquake-triggered landslide in 1913 (Ambraseys and Bilham, 2014). Now that the dam exists, a question that must be addressed is whether the dam can safely survive the largest credible earthquake that has been postulated

for the Garhwal Himalaya, an earthquake approximately 60 times more powerful than for which it was initially designed.

The location of the Tehri dam was conceived in 1949 and proposed as a viable project in 1961 before the formulation of plate tectonics and before it was realized that the Himalaya define a plate boundary. Because no major earthquake had occurred in the preceding 200 years the notion that historical earthquakes exceeding  $M_w=8$  could occur near the dam was initially resisted by engineers. In 1972 the possibility of a great earthquake in the Garhwal Himalaya had still not been fully accepted, and as a consequence a design earthquake of  $M_s=7.2$ , with a design peak ground acceleration of 0.25g, was considered adequate for engineering considerations. The parameters of such an earthquake are equivalent to 2 m of slip on an 80 km x 20 km rupture zone.

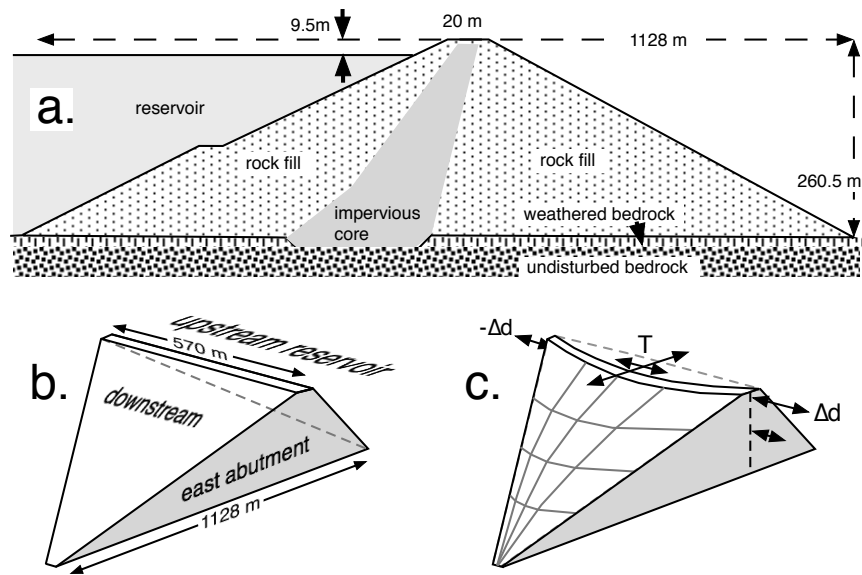


Figure 1a. Schematic section through the central part of the Tehri dam. b. Schematic 3-D view of dam from SE illustrating its tetrahedral form, and c. the fundamental transverse and longitudinal oscillation modes of its crest  $T_t$  and  $T_l$  due to its mass and rheology, and strain amplification  $\Delta d$  of the natural buttresses applied to the dam during strong shaking.

In the two decades following 1980, discussions among engineers, government officials, and seismologists eventually led to agreement that the maximum credible earthquake (MCE) for the Tehri region should be raised from  $M_s=7.2$  to  $M_w=8.5$  corresponding to an earthquake rupture zone measuring 100 km by 200 km with 10 m of slip (Gaur and Valdiya, 1993; Gaur, 2015). An additional realization was that the rupture zone of the hypothesized maximum credible  $M_w=8.5$  earthquake could occur directly beneath (15 km below) the dam, rather than at some arbitrary distance from it laterally (20-100 km). Despite the 60-fold energy increase associated with this increase in maximum credible earthquake from  $M_w=7.2$  to 8.5, and the 15 km proximity of the rupture zone, the design acceleration for the Tehri dam remained unchanged at 0.25g, as it does to this day.

Since the dam's completion in 2006 additional studies have shown that the maximum credible earthquake in this sector of the Himalaya of  $M_w=8.5$  may be too low. The possibility of magnitudes exceeding  $M_w=8.8$  occurring in the region is based on a 500 year or longer absence of great historical earthquakes, the current rate of contraction observed geodetically (18 mm/yr), and the observation that coseismic displacements in some Himalayan earthquakes have apparently exceeded 23 m (Kumar et al., 2006; Schiffman et al., 2012; Stevens and Avouac, 2015; Mugnier et al. 2013). Notwithstanding these larger possible ruptures, for the purposes of this discussion we shall retain the adopted MCE of  $M_w=8.5$ . We shall also ignore the recent discovery of an active fault near the dam (Gupta et al., 2010), which is unlikely to slip in isolation, but is very likely to be reactivated in a great earthquake

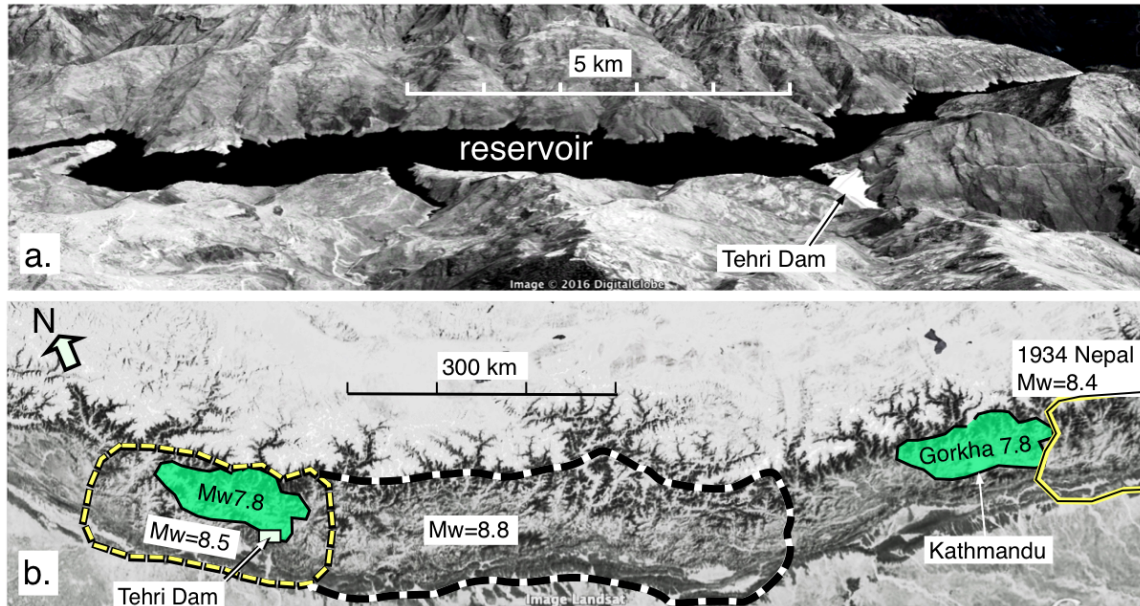


Figure 2. a. Oblique Google Earth view of the Tehri Dam and reservoir from SW in October 2010. b. The location of the dam with the Gorkha rupture zone superimposed on the Garhwal Himal. Strong motion records from rock sites near Kathmandu offer a template for possible future accelerations for a  $M_w=7.8$  earthquake near the Tehri Dam. A possible rupture area for the proposed  $M_w=8.5$  maximum credible earthquake (MCE) is dashed, with the conjectural rupture zone of the enigmatic  $M_w \approx 8.8$  June 1505 earthquake extending eastward into western Nepal. (Google Earth Imagery).

The adoption of a MCE magnitude of  $M_w=8.5$  brought with it a further consideration for engineers - an extended duration of strong shaking. A  $M_w=7.2$  earthquake can rupture in 20 seconds (a rupture length of 60 km with a rupture propagation velocity of 3 km/sec), but a  $M_w=8.5$  earthquake, unless it propagates bilaterally would have a duration of 60-80 s (200-240 km along-arc length, and 80-100 km across-arc width). Because continued shaking leads to progressive failure in earth and rock fill dams, critics argued that these early computer test models of shaking at 0.25g for 20 seconds were unreasonably short. The wisdom of retaining 0.25 g as an upper limit to anticipated accelerations was further questioned, some suggesting 0.56 g or even 1.0 g (Brune, 1993). This was countered by the curious proposal by some seismologists that Peak Ground Acceleration (PGA) should be replaced by the notion of EPGA or "effective peak ground motion". EPGA is derived by omitting the largest 10% of all observed peaks in acceleration data, yielding

an EPA typically half the value of PGA. EPGA in simple terms, discards the peak accelerations that are actually experienced by a structure, in favor of a truncated accelerogram for the sake of computational simplicity. The ramifications of this physically unrealistic redefinition of the Tehri design acceleration are discussed by Iyengar (1993).

The Tehri dam is now a reality, and the two-decade discussion concerning its design is moot. Seismologists and engineers concerned with downstream population safety have now shifted their attention to calculations posed to identify what combination of acceleration, velocity, displacement and duration would compromise the stability of the dam. These synthetic tests are designed to determine the precise input conditions that can dynamically strain the dam beyond its elastic limit. The dam has an impervious core surrounded by a stabilizing envelope of rock aggregate, and the simulations must

determine under what conditions its base, and lower levels spread laterally, thereby lowering its crest, or weaken or rupture its core. Such deformation would permit overtopping, and ultimately, under sufficient shaking, a breach and collapse of the dam. Testing the dam is undertaken using computer models. The modeling of the dynamic behavior of the dam requires engineering insights concerning its geometry

and the strength of its materials, but the realism of synthetic tests depends on the spectral content and duration of seismic shaking used as input to the models. The remainder of this article discusses the intensity and instrumental data from the Nepal 1934 and Gorkha 2015 earthquakes that provide possible constraints on future input to synthetic models of future shaking of the dam.

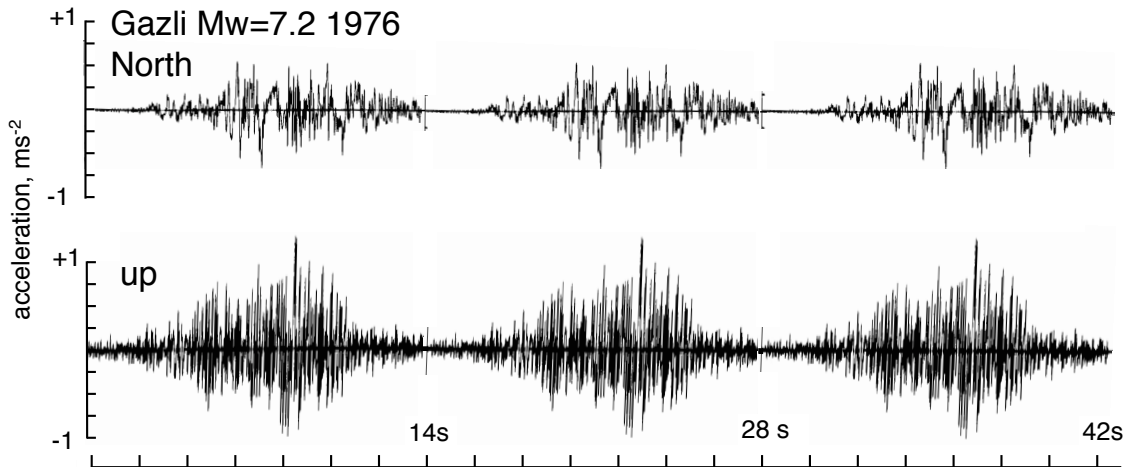


Figure 3 The north and up accelerograms from Karakyr point for the 1976 Gazli earthquake. The 14s record was triplicated to emulate a 42 s duration earthquake (!).

### The search for the perfect seismogram

Preferred dynamic models of the Tehri Dam use as input the seismograms of existing earthquakes. In the mid 1990s, in the absence of a suitable instrumental Mw=8.5 earthquake record, the seismogram from the 1976 Gazli Mw=7.2 earthquake was used in input in computer simulation of dam integrity. The record has the advantage of peak accelerations of 1.3 g vertically and 0.72g horizontally (larger than expected) but has the noted disadvantage that the seismogram has a duration of only 14 s, and although it was associated with 3.3m of slip (Hartzell, 1980) it is not a shallow thrust type of earthquake as expected near the Tehri Dam. The dam survived the synthetic Gazli test, but critics noted that the dam was beginning to respond unfavorably to shaking 8s into the test, reaching a maximum

response to shaking after 12 s, near the end of the record. To overcome criticism that the brevity of the seismic record thwarted a true test of prolonged shaking, the Gazli record was artificially extended by the unusual expedient of running the seismogram through the model three times end-to-end (Ramachandran, 2001). The resulting 42-s-duration synthetic seismogram with its three strong pulses of shaking and two intervening lulls (Figure 3), apart from still being too short, has no resemblance to seismic shaking during a real Mw=8.5 earthquake. The Gazli results were viewed with scientific dismay (Gaur, 2015), but they satisfied the government-appointed committee (a single engineer), who advised the government that the dam design was adequate to permit completion.

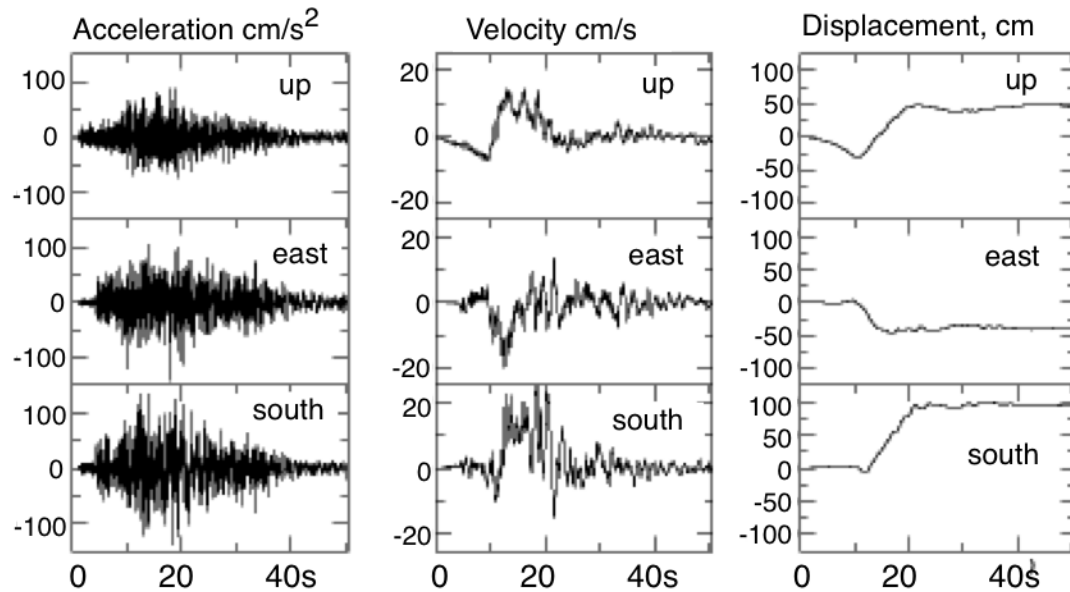


Figure 4. Strong motion record from the 1985 Mw=7.6 Michoacan earthquake with >6 m of slip, showing acceleration, velocity and displacement  $\approx 20$  km above the rupture. (from <http://eqseis.geosc.psu.edu/~cammon/>)

A more thorough synthetic test of the integrity of the dam was undertaken by Sengupta (2010) who used as input a seismogram from the 1985 Mexico City (Michoacan) Mw=7.6 earthquake. This earthquake (Medoza and Hartzell, 1989) more closely emulates what might be anticipated in the Himalaya in that it was recorded in the hanging wall of a subduction zone earthquake on the Mexico Pacific coastline. The subsurface rupture underwent 6 m of coseismic slip, that was manifest as 1 m of surface slip recorded by the accelerometer. By scaling the observed accelerations from 0.22 g to 0.45 g (a linear multiplication of wave amplitude) he more closely emulated the possible effects of an Mw=8.5 earthquake on the Tehri Dam, however, the record remains short, and in models he used only the first 23s of the 50 s available. Using four well-documented modelling procedures he was able to synthetically induce a range of non-recoverable lateral displacements in the body of the dam, with amplitudes from 0.1 m (negligible) to 7.8 m (perilous), the largest of which would lead to partial settlement of the crest of the dam. The

results from some models agreed better than others, but none included the free surface amplification of the valley sides, or the increased transient shear loading from the tsunami in the reservoir north of the dam.

Three shortcomings in the 42-s-long Michoacan earthquake are that it does not emulate the  $\leq 80$  s of shaking anticipated in a Mw=8.5 Himalayan earthquake, the  $\approx 10$  km closer proximity of the Himalayan rupture surface, or the probably much larger ( $\approx 10$  m) southward offset anticipated in a great Himalayan earthquake. In the past decade two great earthquakes have yielded strong motion data from near their rupture zones: Maule 2010 Mw=8.8 and 2011 Tohoku M=9.0. However, not only are their magnitudes too large to constitute a fair test for a Mw=8.5 Himalayan earthquake, they are recorded by strong-motion instruments near the ocean/continent boundary and hence are not good templates for a Himalayan event. Strong-motion records from these earthquakes are equivalent to recording a Himalayan earthquake from instruments placed in southern Tibet.

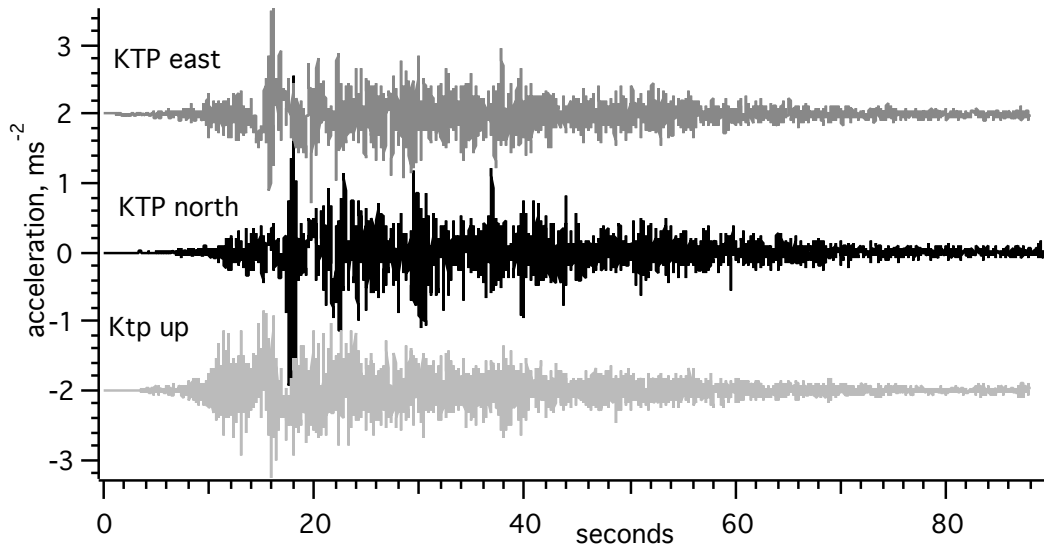


Figure 4. Accelerogram from bedrock site KTP on the SW edge of the Kathmandu Valley for the Gorkha earthquake (Takai et al., 2016). The north and up traces have been offset by  $2 \text{ ms}^{-2}$ , and advanced by 2 s to reduce peak overlap between traces.

The 1999 ChiChi  $M_w=7.6$  and 2015 Gorkha  $M_w=7.8$  earthquakes, however, yielded strong motion records of ground motion above a décollement rupture similar to that which will be experienced by the Tehri Dam. Both records include "fling" (Abrahamson, 2006) and "directivity" (Somerville et al., 1997). Fling in the Gorkha earthquake in some locations may have exceeded 2 m, but only 1.5 m was recorded at the location of the available strong motion records (Figure 5a). The Chichi earthquake ruptured to the surface, whereas the Gorkha earthquake stopped in the subsurface, coincidentally near Kathmandu where the only strong motion records from the Gorkha earthquake were obtained. The effects of fling and directivity are discussed below.

In figure 2b the Gorkha earthquake rupture is superimposed on the Garhwal Himalaya

with its northern edge corresponding to the zone of seismic decoupling there. In this case, the Tehri Dam has approximately the same geometrical relationship to this hypothetical rupture, as does Kathmandu. Hence the strong motion records available from the Gorkha earthquake are almost ideally suited to examining the response of the Tehri Dam to a  $M_w7.8$  incomplete rupture in the Garhwal Himalaya, with rupture terminating near the dam. Accelerations approach 0.25 g for only a few tens of seconds. Thus, given the 2d simulations of Sengupta (2010), the Tehri Dam's design criteria are adequate to survive a Gorkha type earthquake. This must be considered good news. But how representative are the acceleration records for the Gorkha earthquake? Can they be scaled for a larger earthquake, and if so how?

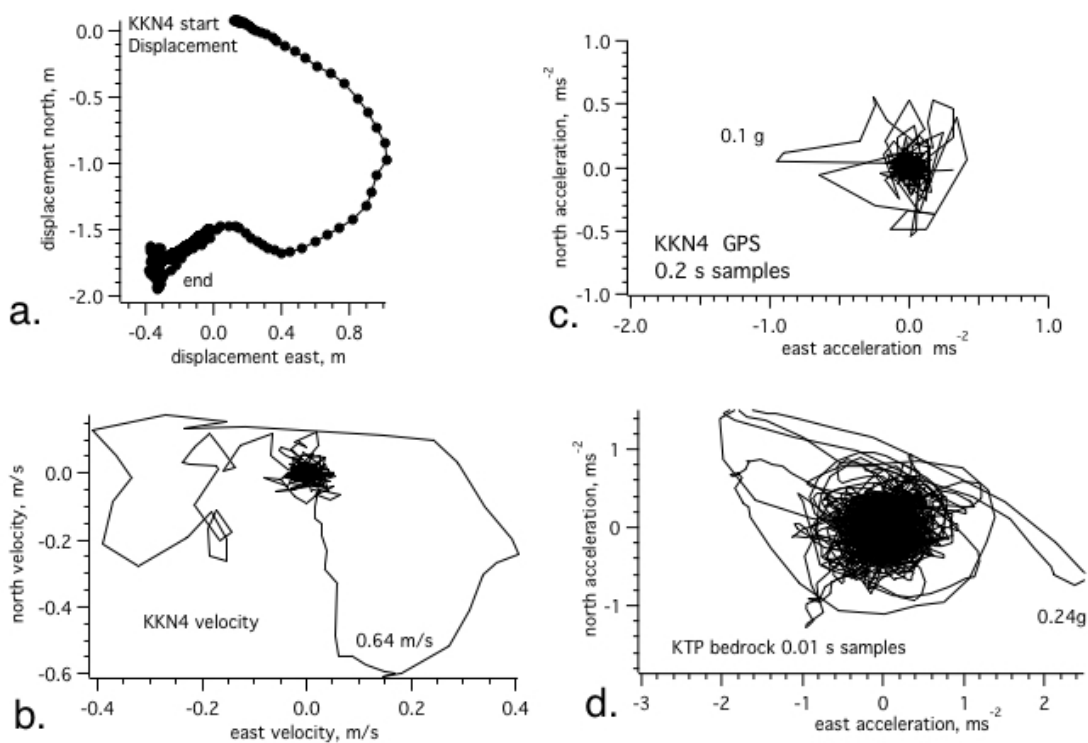


Figure 5 Bedrock motions from the southern edge of the Gorkha rupture displayed as hodograms- map views of horizontal components. **a.** GPS positions sampled every 0.2s at point KKN4 reveal the wholesale 1.5 m SSW displacement of the surface rocks of Nepal to the SSE over the Indian plate. Simultaneously the point rose 1 m (Galetzka et al. 2015). The horizontal displacement is known as "fling" because of its non-recoverable offset (in this case more than 1.5 m. **b.** KKN4 GPS velocity is the derivative of 5a. **c.** KKN4 acceleration, the derivative of 5b **d.** KTP acceleration (Takai et al., 2016).

### Gorkha ground motions

As mentioned earlier, the instrumental accelerations observed in the Gorkha earthquake (Figure 4 & 5) were lower than expected for a  $M_w=7.8$  earthquake elsewhere (Martin et al, 2015; Dixit et al., 2015; Goda et al., 2015). Of the five strong motion accelerometers that recorded the earthquake, four were on the thick sediments of the Kathmandu valley and recorded amplified and prolonged resonance (Dixit et al., 2015; Takai et al, 2015), and are thus of no utility for Tehri Dam studies. Accelerations from the one instrument on bedrock (KTP in Takai et al, 2015), on the SW edge of the valley are shown in Figure 5 as an east-north vector hodogram (Figure 5d). The plot emphasizes the relatively brief period near the time of the fling pulse when accelerations significantly exceeded 0.1 g.

A GPS unit at KKN4 sampling positions 5 times per second on the northern edge of the valley recorded somewhat lower accelerations (Figure 5c) due its lower sampling frequency. Unfortunately there were no instrumental records above the rupture zone of the Gorkha earthquake except those near Kathmandu. Goda et al. (2015) illustrate the difficulty in emulating mezzocentral accelerations from existing theory, which are uniformly unable to accurately characterize accelerations above a subhorizontal rupture. Could the low observed accelerations have been confined to the Kathmandu basin and its environs, where the influence of basin interaction was large? Could the accelerations have been influenced anomalously by the mechanics of



stopping phases near the southern edge of the rupture?

A partial answer this question comes from observed macroseismic intensity observations from above the rupture. With the exception of the study of Martin et al., (2015), at the time of writing no comprehensive survey of intensities of the mezzoseismal zone has been published. Figure 6 shows some of their data omitting

many from the Kathmandu Valley. Observed intensities ( $EMS\ 6.6\pm 0.5$ ) made in traverses across the rupture indicate that accelerations probably did not exceed 0.2 g except on ridges ( $EMS\leq 8$ ). Thus both instrumental data and macroseismic data indicate that accelerations above the Gorkha rupture on average did not exceed 0.25 g. This bodes well for the Tehri Dam should it enjoy a similar earthquake.

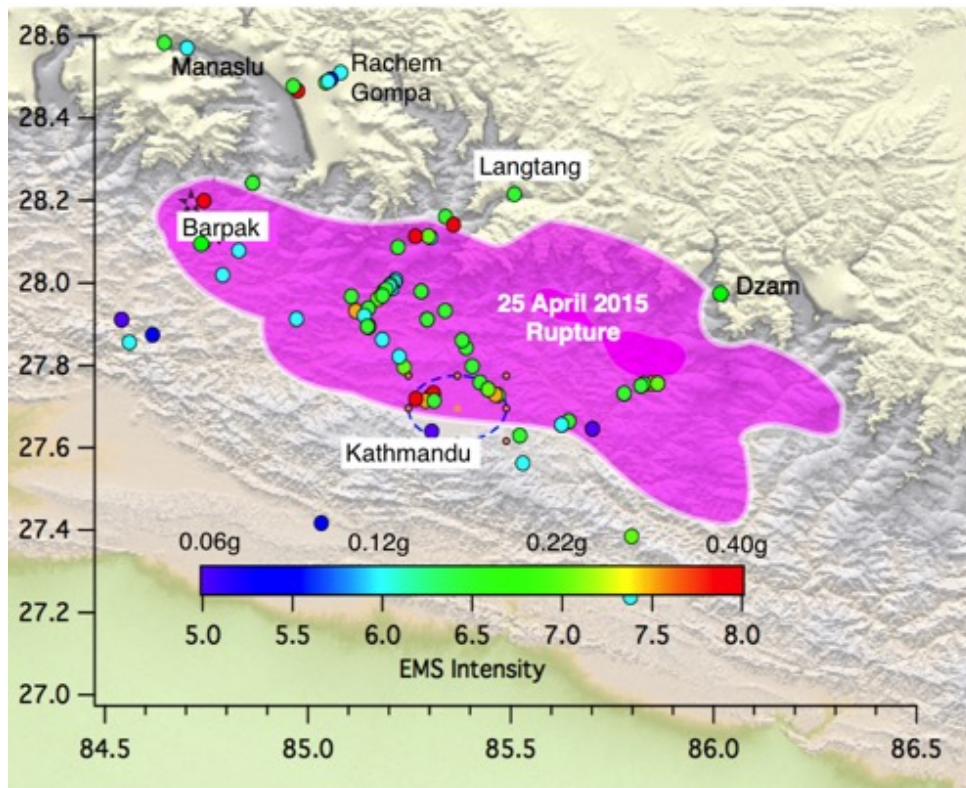


Figure 6. EMS Intensities assessed in traverses across the Gorkha rupture. The mean EMS value for 45 observations above the rupture is  $EMS\ 6.6\pm 0.5$ . Intensity  $\geq 8$  was observed on ridges. The data suggest accelerations of  $0.2\pm 0.1g$  prevailed above the rupture.

### Fling pulse and the rupture process

The most significant difference between seismograms used in previous simulations of Tehri Dam integrity and the newly available strong motion records from the Gorkha earthquake is the presence of the large translation pulse (fling) that arrives 27 seconds after the mainshock. In the Michoacan record it approaches 1 m. In the Gorkha record it exceeds 1.5 m (Fig 5a).

Unfortunately the double-integrated time series emulation of horizontal displacements from data in Figure 4 (not shown) is marred by apparent tilt of the sensor during the record. The 1.5-m -fling pulse is caused by the southward displacement of the Himalaya over the Indian plate, the process that permits the Indian plate to descend beneath southern Tibet. The fling is manifest as an incremental displacement at every point above the rupture, which in the case of the



Gorkha earthquake has been precisely quantified by geodetic measurement before and after the earthquake (e.g. Lindsey et al., 2015). Maximum displacement occurs on the rupture surface at 10-15 km depth, and had the rupture propagated uniformly to the frontal thrusts at the surface, displacements throughout the rupture (with the exception of regions near the northern, eastern and western edges) would have closely matched these maxima because the earth's surface is traction-free.

Rupture propagated from the nucleation region 80 km to the NW of Kathmandu towards the city at 2.5-3 km/s slowing as it passed (Hayes et al., 2015). The physics of the slip process is currently the subject of much research and no single mechanism is presently preferred (e.g. Andrews and Ben Zion, 1997, Anoshehpour and Brune 1999). Melting, dynamic separation, and fluid pressurization have been invoked as a mechanism for an instantaneous reduction in friction to close to zero. Very low friction is necessary for the base of the Himalaya to be momentarily freed from the Indian plate beneath it and to respond to the compressional strain that propels overlying rocks southward. It is certain that only a small patch of the entire rupture surface is in motion at any one moment, and that displacement is rapid and able to nucleate additional seismic waves as it slips. Thus during rupture, myriads of smaller shocks are generated (Avoûac et al., 2015). These initiate compressional p-waves and transverse shear s-waves that radiate from breaking points on the rupture zone in all directions at velocities of 3.5-7 km/s. Waves radiating in the direction from which the propagating rupture arrived fall far behind the rupture front, but those heading in the direction of the rupture are barely able to outpace the rupture, and hence may arrive as a burst of energy slightly before the arrival of the rupture front. Should the s-wave velocity equal the propagation velocity an extreme scenario in which the slow moving s-waves from numerous secondary propagation shocks all arrive at the same

time at a point resulting in constructive interference and significantly amplified surface displacement. The doppler-like compression of forward propagating energy is known as *directivity*.

Despite the propagation front traveling SE towards Kathmandu, a condition optimum for directivity amplification near Kathmandu, accelerations recorded near the city before the arrival of fling pulse remained below 0.1g.

In the case of the Gorkha earthquake the rupture did not continue to the southern edge of the Himalaya and instead terminated near the southern edge of the Kathmandu valley. Maximum displacements on the rupture north of Kathmandu locally attained 7 m but horizontal surface displacements above this maximum were reduced by elastic compression of surface rocks, which resulted in Poisson's-ratio elastic thickening near Kathmandu, and hence observed uplift of more than 0.8 m

### **The effect on the Tehri Dam of a replica of the Gorkha earthquake.**

We concluded above that the accelerations to which Tehri Dam will be subjected are within the design acceleration of 0.25g if we assume that an incomplete rupture of the Garhwal Himalaya occurs as depicted in Figure 2b. However, the horizontal and vertical fling pulse evident in Figure 5a is larger than in previous emulations - would this not result in unpredictably high stresses in the dam? The following reasoning shows this unlikely. The sickle-shaped translation of the rocks surrounding the Kathmandu basin took 9 s to shift the city 1.5 m to the south, but was mostly complete in 5s seconds (the dots indicate 0.2s increments). This low frequency non-recoverable pulse stimulated the Kathmandu valley sediments into resonance. However, the fundamental resonance of the Tehri Dam is 1-2s. The effect of translating the Tehri Dam 1.5 m to the south in 5-9 s periods is thus unlikely to stimulate failure modes within the dam. Just

as a short stubby building resists damage during slow shaking, the Tehri Dam is apparently immune to the direct effects of a Gorkha-type slip pulse.

The pulse will, however, stimulate a tsunami in the Tehri reservoir which may result in overtopping if the reservoir is close to capacity. It has a 9.5 m freeboard when full, (Figure 1a) but this could increase to more than 100 m were the earthquake to occur when the reservoir is low, rendering overtopping unlikely. This possibility is further reduced by the general east-west trend of the Tehri reservoir which is normal to the probable maximum fling. The semicircular path of the Gorkha fling pulse, were it to be imposed in Garwhal would, however, simulate a significant longitudinal wave in the Tehri reservoir.

The net conclusion is that were a Gorkha type  $M_w=7.8$  earthquake to occur near Tehri it would survive both the high frequency accelerations and its fling pulse. Not considered is a conspiracy of directivity effects, and abutment convergence displacements (Figure 1 c) caused by topographic amplification in the valley that would result in unusually high local amplifications.

## **II. DISCUSSION: Scaling the Gorkha earthquake upward to $M_w=8.5$ .**

It is now possible to develop a synthetic seismogram of arbitrary complexity above a rupture (Rai and Beroza, 2002; Erdik and Durukal, 2003, Raghu Kanth and Iyengar, 2008), and such models permit a wealth of conjectural ruptures to be synthesized. However, such models are limited by the precision of physical insights into the rupture process.

The traditional method that has been used to increase the magnitude of an earthquake input to a synthetic models is to multiply the amplitude of an available strong motion

record by a linear scaling factor. The pitfalls and methods of undertaking scaling are discussed by Bommer & Acevedo (2004) and Watson-Lamprey & Abrahamson (2006). The conversion of the Gorkha earthquake record into a plausible simulation of a  $M_w=8.5$  Himalayan earthquake must realistically account for increased along-strike rupture duration, and the correct adaptation of the record for complete up-dip rupture to the frontal thrusts. The 2015 rupture length ( $\approx 150\text{km}$ ) is only 30-50% shorter than the MCE rupture of 200-300 km, and is very similar to that associated with the 1934 earthquake. Hence along-strike duration requires padding, but does not constitute a significant spectral problem. It is, however, essential to apply a realistically long duration period of strong synthetic shaking to the dam to model such factors such as a pore pressure weakening in the dam structure (Bureau, 2003).

A less easy problem to solve is how to correctly emulate the possibly modified period of the fling pulse. If the duration of the slip pulse in a 10-15 m rupture  $M_w=8.5$  rupture occurred in the same 5-9 s duration as seen in the Gorkha earthquake, the accelerations (and decelerations) would obviously increase accordingly. However, we have some evidence that this may *not* occur from the intensity data in Figure 3. Although mean slip was approximately 3.5 m, and slip locally exceed 6 m, surface displacements on the rupture surface north of Kathmandu did not much exceed 2 m (Lindsey et al., 2015) slightly larger than recorded in Kathmandu, but more than twice that near the epicenter, and over most of the rupture. Despite double the surface slip, EMS intensities near and north of Kathmandu remained the same (Figure 6). A caveat remains, of course, in that the EMS damage scale may not provide a sufficiently precise constraint of both high frequency shaking and monotonic fling.

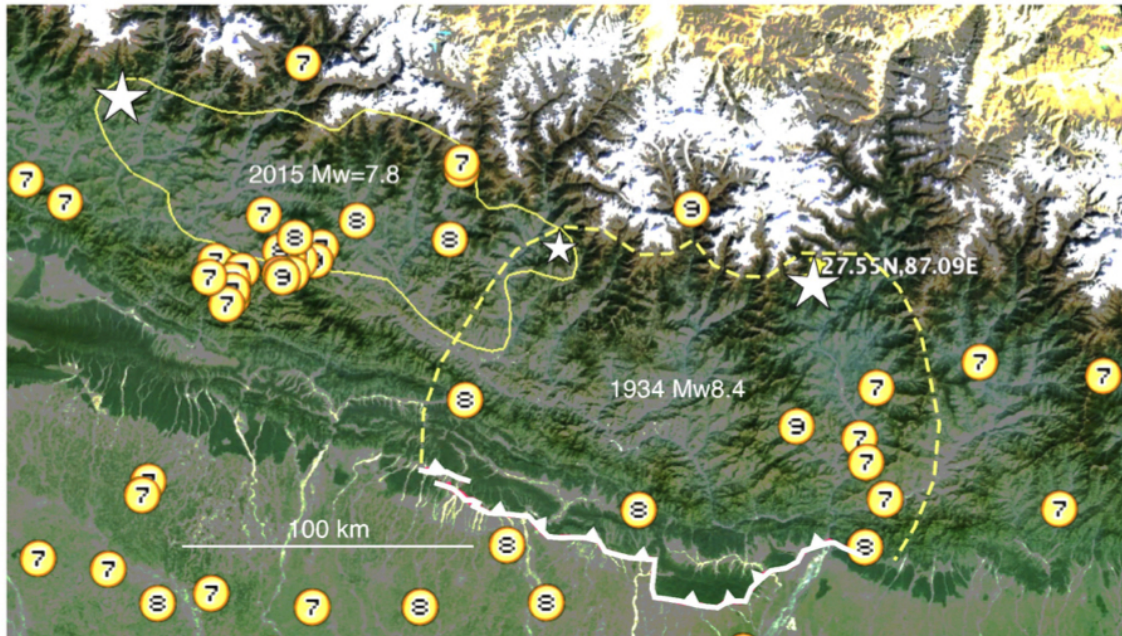


Figure 7 Reported EMS intensities for the Nepal 1934 Mw=8.4 earthquake (Martin and Szeliga, 2004) with a conjectural rupture zone (dashed). Epicenter is from Chen and Molnar (1987) and MFT rupture from Sapkota et al., 2012. Intensities above the 1934 rupture are sparse but average EMS  $7.6 \pm 0.7$ . With the conjectural rupture shown, mean slip in 1934 would be  $\approx 8$  m. (Google Earth image).

A second constraint on whether slip pulse accelerations scale with Himalayan earthquake magnitude comes from the 1934 Mw=8.4 earthquake. The magnitude reported for this earthquake depends on the dip applied to the calculation of magnitude. Earlier magnitudes adopted much larger dip than we now know is appropriate and values of the order of  $8.1 < Mw < 8.2$  have commonly been cited. The value used here (Mw=8.4) is that derived by Chen and Molnar (1989). Unfortunately, however, only eight intensity observations are available from above the rupture of the 1934 earthquake. They yield an average value of EMS  $7.6 \pm 0.7$  including a single EMS=9. Based on this magnitude and the rupture area shown in figure 7 we infer that mean slip in the earthquake as 8 m.

From this we conclude that an approximate doubling in décollement slip from  $\approx 3.5$  m to  $\approx 8$  m results in a one unit increase in EMS Intensity, which corresponds to an approximate doubling in acceleration. The sparsity of macroseismic data for the 1934 earthquake, and the tendency for reports of

shaking to focus on the worst-damaged structures in villages, suggests that the factor may be less than 2. In contrast, a doubling in surface slip between the southern edge of the rupture, and the central rupture in the Gorkha earthquake was accompanied by no discernable increase in EMS Intensity, possibly related to the absence of a diversity in building styles above rupture suited to identifying degrees of damage near EMS intensity 7. For the 1934 Mw=8.4 earthquake a single intensity 9 observation is reported (PGA of 0.65-1 g) and this value, as in anomalously high values observed for the Gorkha earthquake, may be due to the effects of ridge amplification.

An implication of acceleration being proportional to slip amplitude is that the slip pulse duration is independent of slip amplitude. Alternatively if acceleration remains constant in the presence of increasing slip, slip-pulse duration must increase with slip amplitude. It would be of value to apply additional data to distinguish these two end members. In view of the

conflicting conclusions related to scaling the fling pulse in the Gorkha record to a Mw=8.5 earthquake, a conservative approach would be to double the amplitude throughout of the record. This would peak raise accelerations to  $\approx 0.5$  g while maintaining the same spectral content.

### III. CONCLUSIONS

In this article I review the potential utility of using the Gorkha earthquake as a template for future shaking of the Tehri Dam in the Garhwal Himalaya. Based on the results of published 2d synthetic models, I conclude from the one available rock accelerogram for the Gorkha earthquake (KTP, Takai et al., 2016), that the dam will survive a similar Mw7.8 earthquake unscathed. The possibility of the dam sustaining damage in a much larger earthquake requires using a version of the Gorkha record appropriately scaled to longer duration and significantly larger fling. In the Gorkha record fling was 1.5m, but the non-recoverable southward translation of the dam in a future great earthquake may exceed 15 m.

Inferred slip in the Mw8.4 Nepal 1934 earthquake was roughly double that recorded in the Mw7.8 Gorkha 2015 earthquake and mean rupture intensities were  $EMS = 7.6 \pm 0.7$  and  $EMS = 6.6 \pm 0.5$  respectively. From these ratios we deduce that fling pulse accelerations may scale linearly with earthquake magnitude. In contrast, no difference could be discerned between intensities in the Gorkha earthquake where surface displacements varied by a factor of two. A conservative approach would be to adopt a linear scaling relationship, because EMS intensities above the Gorkha earthquake were derived from a limited range of building styles, with consequent difficulties in discerning subtle differences in shaking intensity.

Hitherto synthetic 2D simulations of Tehri Dam shaking have been limited to durations of 23s or to artificially unrealistic shaking

with 42s duration. Prolonged cyclic shaking for 60 s or more may lead to progressive failure associated with non-linear deformation, and pore pressure increase that may or may not occur. It is timely to subject the Tehri Dam to a full 3D synthetic computer simulation. Scaled and lengthened versions of the Gorkha earthquake accelerograms have known inadequacies, but they appear currently to provide a more realistic input to such models than any available hitherto.

### References

- Abrahamson N. A. (2002) Velocity pulses in near-fault ground motions. In: *Proceedings of the UC Berkeley—CUREE symposium in honor of Ray Clough and Joseph Penzien*, Berkeley, CA; 2002. 40–41
- Adikhari, B. R. (2009), Tehri Dam: an engineering marvel. *Hydro Nepal*, **5**, 26–30.
- Ambraseys, N. and Bilham, R. (2012), The Sarez-Pamir Earthquake and Landslide of 18 February 1911 *Seism. Res. Lett.* March, **83**(2), 294–394, doi:10.1785/gssrl.83.2.294
- Andrews, D. J., and Y. Ben-Zion, (1997) Wrinkle-like slip pulse on a fault between different materials. *J. Geophys. Res.*, **102**, 553–571.
- Anooshehpour, A., Brune, J. N. (1999), Wrinkle-like Weertman pulse at the interface between two blocks of foam rubber with different velocities, *Geophys. Res. Lett.*, **26**, 2025–2028.
- Avouac, J.-P., L. Meng, S. Wei, T. Wang, and J.-P. Ampuero, 2015, Lower edge of locked Main Himalayan Thrust unzipped by the 2015 Gorkha earthquake, *Nature geoscience* doi:10.1038/NGEO2518.
- Bommer, J. J. & A. B. Acevedo (2004), The use of real time earthquake accelerations as input to dynamic analysis, *J. Earthq. Eng.* **8**(1), 43–91, DOI 10.1080/13632460409350521.
- Brune, J. N., (1993) The seismic hazard of the Tehri dam, *Tectonophysics*, **217**, 281–286.

- Bureau, G. J., (2003), Dams and Appurtenant Facilities, in *Earthquake Engineering Handbook*, ed Wai-Fah Chen and Charles Scawthorn, CRC Press 26.1-6.47, Washington.
- Burks L. S. and J.W. Baker (2015), A predictive model for fling-step in near-fault ground motions based on recordings and simulations, *Soil dynamics and Earthquake Engineering*, **80**, 119-216
- Chen W. P and P. Molnar (1983) Focal depths and fault plane solutions of earthquakes under the Toibetan Plateau, *J Geophys. Res*, 88 B2, 1180-1196.
- Dixit, A. M, Adam T. Ringler, Danielle F. Sumy, Elizabeth S. Cochran, Susan E. Hough, Stacey S. Martin, Steven Gibbons, James H. Luetgert, John Galetzka, Surya Narayan Shrestha, Sudhir Rajaure, and Daniel E. McNamara (2015), Strong-Motion Observations of the M 7.8 Gorkha, Nepal, Earthquake Sequence and Development of the N-SHAKE Strong-Motion Network *Seism. Res. Lett.*, **86**, 1533-1539, doi:10.1785/0220150146
- Erdik, M., and E. Durukal (2003), Simulation of strong ground motion, *Earthquake Engineering Handbook*, ed Wai-Fah Chen and Charles Scawthorn, CRC Press 6.1-6.67, Washington.
- Galetzka, J., D. Melgar, J. Genrich, J. Geng, S. Owen, E. Lindsey, X. Xu, Y. Bock, J.-P. Avouac, L. Adhikari, B. Upreti, B. Pratt-Sitaula, T. Bhattarai, B. Sitaula, A. Moore, K. Hudnut, W. Szeliga, J. Normandeau, M. Fend, M. Flouzat, L. Bollinger, P. Shrestha, B. Koirala, U. Gautam, M. Bhattarai, R. Gupta, T. Kandel, C. Timsina, S. Sapkota, S. Rajaure, and N. Maharjan, 2015, Slip pulse and resonance of the Kathmandu basin during the 2015 Gorkha earthquake, Nepal, *Science* **349**, 1091.
- Gaur, Vinod K. and Valdiya, K. S. (1993) *Earthquake Hazard and Large Dams in the Himalaya* Indian National Trust for Art and Cultural Heritage, New Delhi, ISBN 81-900281-2-X
- Gaur, V. K., (2015). Geoethics: Tenets and Praxis: Two Examples from India, Ch 12 in *Geoethics, Ethical Challenges and Case Studies in Earth Sciences*, 141-160. doi:10.1016/B978-0-12-799935-7.00012-5
- Goda K, Kiyota T, Pokhrel RM, Chiaro G, Katagiri T, Sharma K and Wilkinson S (2015) The 2015 Gorkha Nepal earthquake: insights from earthquake damage survey. *Front. Built Environ.* 1:8. doi: 10.3389/fbuil.2015.00008
- Gupta, S., P. Mahesh, K Sivaram and S. S. Rai (2012), Active fault beneath the Tehri Dam, Garhwal Himalaya - seismological evidence, *Current Science*, **103**, (11), 1343-1347
- Hartzell, S., (1980). Faulting Process of the May 17 Gazli, USSR Earthquake, *Bull. seism. Soc. Amer.* 70(5) 1715-1736
- Iyengar, RN (1993) How safe is the proposed Tehri dam to earthquakes *Current Science* (Bangalore), **65** (5), 384-392
- Lindsey, E. O., R. Natsuaki, X. Xu, M. Shimada, M. Hashimoto, D. Melgar and D. T. Sandwell, Line of Sight Displacement from ALOS-2 Interferometry: Mw 7.8 Gorkha Earthquake and Mw 7.3 Aftershock, *Geophys. Res. Lett.*, **42** (2015), doi:10.1002/2015GL065385
- Mai, P. M., and G. C. Beroza, (2002) A spatial random field model to characterize complexity in earthquake slip, *J. Geophys. Res.*, **107**(B11), 2308, doi:10.1029/2001JB000588, 2002.
- Martin. S., and W. Szeliga, (2010), A catalog of felt intensity data for 589 earthquakes in India, 1636-2009, *Bull. Seism Soc. Amer*, 100, 2, pp. 536-569, 2010
- Martin, S.S. Susan E. Hough, and Charleen Hung (2016) Ground Motions from the 2015  $M_w$  7.8 Gorkha, Nepal, Earthquake Constrained by a Detailed Assessment of Macroseismic Data, *Seism. Res. Lett.* **86**, 1524-1532, doi:10.1785/0220150138
- Mendoza, C and S. H. Hartzell (1989). Slip distribution of the 19 September 1985 Michoacan, Mexico, earthquake: Near-source and teleseismic constraints. *Bull. seism. Soc. Amer.* **79**(3) 655-669
- Mugnier, J.-L., A. Gajurel, P. Huyghe, R. Jayangondaperumal, F. Jouanne, and B.



- Upreti (2013), Structural interpretation of the great earthquakes of the last millennium in the central Himalaya, *Earth Science Reviews*, **127**, 30-47.
- Hayes, G.P., W. Barnhart, R. Briggs, W. Yeck, D.E. McNamara, D. Wald, J. Nealy, H. Benz, R. Gold, K. Jaiswal, K. Marano, P. Earle, M. Hearne, G. Smoczyk, L. Wald, and S. Samsonov (2015). Rapid Characterization of the 2015 Mw 7.8 Nepal (Gorkha) Earthquake (2015). *Seism. Res. Lett.* 86 (6), 1557-1567
- Kamai, R., N. Abrahamson, R. Graves (2014) Adding fling effects to processed ground-motion time histories, *Bull Seismol Soc Am*, 104 (4) (2014), pp. 1914–1929
- Kumar, S., S. G. Wesnousky, T. K. Rockwell, R. W. Briggs, V. C. Thakur, and R. Jayangondaperumal (2006). Paleoseismic evidence of great surface rupture earthquakes along the Indian Himalaya, *J. Geophys. Res.* 111, B03304,
- Lindsey, E., Natsuaki, R., Xu, X., Shimada, M., Hashimoto, H., Melgar, D., and Sandwell, D., (2015), Line of Sight Deformation from ALOS-2 Interferometry: Mw 7.8 Gorkha Earthquake and Mw 7.3 Aftershock, *Geophys. Res. Lett.*, 42, 6655–6661, DOI:10.1002/2015GL065385
- Raghu Kanth, S. T. G., and R. N. Iyengar (2008), Strong motion compatible source geometry, *J. Geophys. Res.*, 113, B04309, doi:10.1029/2006JB004278.
- Ramachandran, R., (2001), The Tehri Turnaround, *Frontline*, **18** (10), May, 2001
- Sapkota S.N., L. Bollinger, Y Klinger, P Tapponier, Y Gaugemer and D. Tiwani (2006), Primary surface ruptures of the great Himalayan earthquakes in 1934 and 1255. *Nature Geoscience*, 6, 71-76.
- Sengupta, A., (2010) Estimation of permanent displacement of the Tehri Dam in the Himalayas due to future strong earthquakes, *Sadhana* (Indian Academy of Sciences), **35**(3), 373-392.
- Stevens V. L., and J. P. Avouac, (2015), Interseismic coupling of the main Himalayan Thrust, *Geophys. Res Lett* 42 5828-5837.
- Schiffman, C., B.S. Bali, W. Szeliga, and R. Bilham, Seismic slip deficit in the Kashmir Himalaya from GPS observations, *Geophys. Res. Lett.*, 40, 5642-5645 (2013) DOI: 10.1002/2013GL057700
- Takai, N., M. Shigefuji, S. Rajaure, S. Bijukchhen, M. Ichiyanagi, M.R. Dhital, T. Sasatani, (2016) Strong ground motion in the Kathmandu Valley during the 2015 Gorkha, Nepal, earthquake, *Earth, Planets and Space*, 68:10 doi:[10.1186/s40623-016-0383-7](https://doi.org/10.1186/s40623-016-0383-7)
- Watson-Lamprey, J and N. Abrahamson (2006), Selection of ground motion time series and limits on scaling. *Soil dynamics and Earthquake Engineering*, **26**, 477-482

Boulder, Colorado, USA  
16 March 2016