GROUNDWORK

Furthering the Influence of Earth Science

Nepal at Risk: Interdisciplinary Lessons Learned from the April 2015 Nepal (Gorkha) Earthquake and Future Concerns

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INTRODUCTION

In response to the devastation caused by the 25 April 2015 M_W 7.9 Nepal (Gorkha) earthquake and its aftershocks, the Geological Society of America convened an interdisciplinary session at its 2015 Annual Meeting in Baltimore. The forum allowed researchers from diverse disciplines to exchange information and develop meaningful paths toward reducing the societal impacts of future large earthquakes in the Himalayan region. Major seismic hazards exist near Kathmandu and along the Himalayan front due to incomplete rupture of the Main Himalayan Thrust (MHT) (Avouac et al., 2015; Bendick et al., 2015; Elliott et al., 2015; Lay, 2015) and thousands of co-seismic landslides (Andermann et al., 2015; Gallen et al., 2015; Ohja and DeCelles, 2015; Poudel, 2015). Surprisingly, the 2015 event ruptured a limited region. Given shortening rates and interseismic geodetic indications that the MHT is almost uniformly locked along strike, larger earthquakes may occur along the collision zone.

GEOLOGICAL FRAMEWORK

The 2015 Gorkha earthquake occurred within the India-Eurasia convergent plate boundary, defined by the >2500-km-long Himalayan orogenic system. Major Himalayan faults sole into the MHT, a pervasive décollement that separates the down-going Indian plate from the Himalayan orogenic wedge (Brown et al., 2015). Above the MHT, the Lesser Himalayan Duplex is the locus of an ~50-km-wide seismogenic zone of predominately moderate earthquakes, up-dip of which the MHT has low background activity but intermittent large slip events (Khattri and Tyagi, 1983).

The challenge of the rugged and steep terrain of the Himalayas, coupled with its large size, have resulted in an incomplete understanding of its paleoseismicity and tectonic history. Unknowns include the northward extent of the Indian craton prior to collision (Lippert et al., 2015) and the role of previously unrecognized or underappreciated fault systems that accommodated convergence in historical times (Taylor and Murphy, 2015). Segmentation of the MHT is also unclear. Structural variations along the Himalayas control the extent of rupture of large earthquakes, and the convergence rate is not constant. The paleoseismic record is limited to ground-rupturing events (Wesnousky et al., 2015); the Gorkha earthquake left little surface record that would be identified by trenching. Models of the Himalayan seismic cycle based on only mapped surface ruptures lead to misfits between geodetic rates and estimated recurrence intervals.

Space-geodetic measurements of present-day strain accumulation across active fault systems directly test structural geological models. Earthquakes help to illuminate detailed fault geometry, but event observables must be interpreted in context. In the past, verification of geometric and kinematic relationships depended on rare earthquake occurrences on a fault. Space-geodetic and 3D fault-geometric data will need to be integrated and made available to earth scientists prior to an earthquake. Novel integration techniques may result in quicker and better hazard estimation.

EVENT INFORMATION FROM SEISMOLOGY AND GEODESY

The Gorkha earthquake occurred on Saturday, 25 April 2015, at 11:56 NST, with an epicenter ~75 km WNW of Kathmandu (e.g., Avouac et al., 2015; Lay, 2015). The event started along the eastern side of a millennial-scale seismic gap and ruptured eastward to the 1934 Bihar-Nepal earthquake zone. It did not break to the surface as in 1934, which leads to concern about limited paleoseismic recognition of past events (Bendick et al., 2015; Wesnousky et al., 2015; Upreti, 2015).

Interseismic strain could proceed to the sub-Himalaya via post-seismic creep along the unruptured portions of the MHT, or a large earthquake could occur along the shallower portion of the MHT, feeding slip to the surface (Wesnousky et al., 2015). Another major earthquake is expected near Kathmandu, because the Gorkha event ruptured only a portion of the MHT and its up-dip region remains locked with minor afterslip occurring south of Kathmandu (Avouac et al., 2015; Bendick et al., 2015; Elliott et al., 2015). Rupture of a shallower, highly strained portion of the MHT may involve higher stress drop failure and possibly

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stronger ground shaking as a result. Three-dimensional visualization approaches linking framework- and event-analysis using seismic, geodetic, and structural data indicates that initial seismological data failed to constrain the geometry of the source fault and the reported uncertainties are unrealistic (Carena and Verdecchia, 2015).

Among the large unknowns are the details of the subsurface structure in Nepal. A systematic program of reflection seismic profiling and targeted 3D reflection imaging that spans past and potential future rupture zones would help assess continuing hazard (Brown et al., 2015). This should include partnerships with Nepal (Upreti, 2015) and build upon both existing resources, including dense portable seismic recording systems that reduce costs. The focus should be on fault-system geometry and structures that may control rupture segmentation and for time-lapse imaging for rupture zone reflectivity.

DAMAGE

The Gorkha earthquake caused ~9,000 deaths and ~25,000 injuries (Gallen et al., 2015). The destruction was extensive for larger structures in Kathmandu (Acharya et al., 2015; Poudel, 2015), but moderate ground motions limited urban impact. Destabilized hillslopes and weakened soil horizons present an ongoing threat (Andermann et al., 2015; Gallen et al., 2015). More than 60% of the villages in central Nepal, which are located on near-threshold or threshold dip slopes, are at high risk (Ojha and DeCelles, 2015). The main industry affected by the earthquake is agriculture, which is the primary occupation of rural communities, even along steep Himalayan slopes (Poudel, 2015). More than 6,000 schools collapsed, but because the earthquake occurred on a Saturday, the vulnerability of most Nepali schools remains underappreciated (Acharya et al., 2015).

Nepali national capacity is building (Upreti, 2015). Acharya et al. (2015) discussed the Kathmandu Valley Earthquake Risk Management Project, initiated in 1995 by the National Society for Earthquake Technology of Nepal and GeoHazards International to train local masons to retrofit 300 schools. Ninety percent of these schools are in areas affected by the Gorkha earthquake, and all survived without significant damage. Nepal plans to repair collapsed schools at a rate of 1,200/year, a massive economic and social challenge because time pressure is at odds with construction training and standards. Overcoming local apprehension of retrofitting and building confidence in Nepali communities regarding geosciences education requires major effort. Stone masonry houses are common throughout the Himalayas, which can collapse instantaneously even during moderate earthquakes. Inexpensive ways to retrofit and design these homes will save lives.

A GIS-based inventory of natural resources and crop production practices in the region affected by the earthquake was proposed as a first step in rebuilding rural Nepal (Poudel, 2015). The convergence zone poses a transnational hazard, and opportunities exist to use this event as an impetus to inform decision making in other countries exposed to the potential of large earthquakes. Investments in earthquake disaster response and recovery compared with preparedness and mitigation are unbalanced and require immediate change.

REFERENCES CITED

Acharya, S.P., Dixit, A.M., and Tucket, B.E., 2015, Nepal's school earthquake safety program: Past accomplishments, future challenges: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-14.

Andermann, C., Behling, R., Cook, K.L., Emberson, R., Hovius, N., Marc, O., Motagh, M., Roessner, S., Sens-Schoenfelder, C., and Turowski, J.M., 2015, Landscape response to the M_W 7.9 Gorkha earthquake: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-12.

Avouac, J.-P., Meng, L., Melgar, D., Wei, S., Wang, T., Bock, Y., Ampuero, J.-P., Stevens, V., Galetzka, J., and Genrich, J., 2015, Unzipping of locked MHT by the 2015, M_W 7.8 Gorkha earthquake, Nepal: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-2.

Bendick, R., Mencin, D., Knappe, E., Upreti, B., Aoudia, A., Galetzka, J., and Bilham, R., 2015, Incomplete decollement rupture in the 25 April 2015 Gorkha earthquake: Implications for postseismic processes: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-6.

Brown, L., Behera, L., Hubbard, J., Karplus, M., and Klemperer, S., 2015, Seismic reflection imaging of the Himalayan seismogenic zone: Past experience and future strategies: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 140-1.

Carena, S., and Verdecchia, A., 2015, 3D visualization of geologic, geodetic, and seismic data from the April-May 2015 Nepal, earthquake doublet: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-4.

Decelles, P.G., 2015, Structural-kinematic setting of the 2015 Gorkha, Nepal earthquakes: Lessons from a critically tapered orogenic wedge: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-9.

Elliott, J.R., Jolivet, R., Gonzalez, P., Avouac, J.-P., Hollingsworth, J., Searle, M.P., and Stevens, V., 2015, Geometry of the Main Himalayan Thrust revealed by the Gorkha earthquake: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-5.

Gallen, S.F., Clark, M.K., Niemi, N., Lupker, M., Gajurel, A.P., West, A.J., Lowe, K., and Roback, K., 2015, Coseismic landslide hazards and geomorphic consequences of the M_W 7.8 Gorkha earthquake, Nepal: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-11.

Khattri, K.N., and Tyagi, A.K., 1983, Seismicity patterns in the Himalayan plate boundary and identification of areas of high seismic potential: Tectonophysics, v. 96, p. 281–297, doi:10.1016/0040-1951(83)90222-6.

Lay, T., 2015, Seismological characteristics of the 25 April 2015 M_W 7.9 Gorkha, Nepal earthquake: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-3.

Lippert, P.C., Van Hinsbergen, D.J.J., Huang, W., and Dupont-Nivet, G., 2015, A great greater India: A paleomagnetic perspective on the amount of Cenozoic subduction and underthrusting within the central Himalaya: Geological Society of America Abstracts with Programs, v. 47, no. 7, p. 105-1.

Ohja, T.P., and DeCelles, P.G., 2015, Landslide distribution before and after the 2015 Gorkha earthquakes in central Nepal: Relationships with dip slopes and villages: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-10.

Poudel, D.D., 2015, Development of Nepal Argo-Industrial information systems (NAIS): The first-step in rebuilding Gorkha earthquake devastated rural Nepal: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 140-2.

Taylor, M.H., and Murphy, M., 2015, Segmentation of the Himalayan arc- the effects of collision obliquity on the development of active faults and earthquake potential: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-8.

Upreti, B.N., 2015, Gorkha earthquake 2015 Nepal: Present knowledge and future research direction: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-13.

Wesnousky, S.G., Angester, S., Pierce, I., Fielding, E.J., Chamlagain, D., Upreti, B., Gautam, D., Kumahara, Y., and Nakata, T., 2015, Interpretation of past and ongoing paleoseismic investigations along the Himalayan frontal thrust in context of brief field reconnaissance after the M7.8 April 25, 2015 Gorkha earthquake: Geological Society of America Abstracts with Programs, v. 47, no. 7, abstract 105-7.

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