Reassessment of earthquake hazard in the Himalaya and implications from the 2004 Sumatra–Andaman earthquake

In earlier accounts of seismicity and long-term forecasting of earthquakes, three great earthquakes with magnitude 28, namely 1905 Kangra, 1934 Bihar–Nepal and 1950 eastern Assam in Himalaya and a fourth one, i.e. 1897 western Assam with magnitude Mw 8.0 were recognized (Figure 1). Regions between the rupture zones of these earthquakes were recognized as seismic gaps, which were interpreted to have accumulated potential slip for generating future great earthquakes. In recent years re-examination of old recorded data has led to revision of the magnitudes and rupture zones of these earlier classified great earthquakes, with new information being extracted from the archives for calculating magnitudes of historical earthquakes: 1505, 1803, 1833 and others. GPS and palaeoseismological studies have added another dimension to our understanding of the kinematics of seismogenic faults and seismotectonics.

The great Kangra earthquake of 4 April 1905 was assigned magnitude 8.1 with its rupture zone extending ~300 km from Kangra to Dehra Dun. This magnitude has been recently revised to Mw 7.8 with rupture extending 90 km along the strike; the intensity VIII estimated at Dehra Dun is interpreted as a separate triggered event. The epicentre of
the 1934 Bihar–Nepal earthquake has been relocated to lie near the MHT to the east of Kathmandu in Lesser Himalaya. In an earlier interpretation, the 1897 western Assam earthquake originated on a gentle north-dipping fault propagating south from the Himalayan front to the base of the Shillong plateau, involving thin-skinned tectonics. Re-examination of old observations in more recent studies proposes a steep south-dipping thrust fault, corresponding to the Oldham fault, as the causative fault for the 1897 earthquake. This fault extended to a depth of 43–46 km, implying that the earthquake occurred in an intraplate tectonic environment. The epicentre of the 1950 eastern Assam earthquake with magnitude $M_W 8.6$ was located in the Mishmi Hills on the eastern limb of the eastern syntaxis. Its fault plane solution indicates predominantly thrust faulting in a plane dipping gently to the northwest, with slip along the dip direction.

There are several important earthquakes of the historical past whose magnitudes have been estimated on the basis of critical review of damage scenarios described in the old archival records. An earthquake of magnitude $M_W 7.4$ in 1720 is described from Kumaun. During the 1803 Garhwal earthquake, most severe and extensive damage was reported from Srinagar in Alaknanda valley and Uttarkashi in Bhagirathi valley. The Badrinath and Gangotri temples located ~50 km north of these towns were damaged. Ground failure and liquefaction induced by this earthquake were reported as far south as Mathura in the Yamuna plain. Based on such damage scenario, the 1803 earthquake was assigned magnitude $M 7.7$. The 1833 Nepal earthquake destroyed more than 46000 dwellings, triggered landslides and killed more than 500 people. This earthquake was assigned magnitude $M_o 7.7$, with its epicentre located ~50 north or northeast of Kathmandu, closely corresponding to the epicentre of the 1934 Bihar–Nepal earthquake. The earthquake of 6 June 1505 in southwestern Tibet affected a region extending ~700 km in the northern part of the Great Himalaya from Saga to LoMustang and Kyirong. This earthquake was assigned magnitude $M 8.2$. There is a report of another major earthquake on 6/15 July 1505 in Agra, mentioned in the memoirs of Sultan Baber. The 1505 Kabul earthquake destroyed the ramparts of the Bakhissar fortress and caused extensive damage to Kabul and regions to the south.

The Kabul earthquake and the southwestern Tibet earthquake that occurred during the same year must be two different events, as they lie in two different tectonic plates separated by more than 1200 km. There are historical records of three moderate to large earthquakes in Kashmir. The 1555 and 1885 earthquakes affecting the Kashmir valley are assigned magnitude $M 7.6$ and $M 6.2$, respectively. The 1751 earthquake in the upper Satluj Valley in Tibet was assigned magnitude of 7.2, and the 1713 earthquake, somewhere in Bhutan or Arunachal Pradesh was a large earthquake with magnitude approaching 7.

Palaeoseismological studies carried along the Himalayan Frontal Thrust (HFT) in northwestern Himalaya, India and east-central Nepal have led to the discovery of two mega-thrust-type earthquakes, much larger in size than the historical earthquakes described earlier in the Himalaya. Six trenches were excavated along the HFT front in a segment stretching from Chandigarh to Rannaghar. Analysis of trench exposures indicates a large coseismic displacement along

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**Figure 1.** Outline map of Himalaya showing calendar year and earthquake locations (a) magnitude 7.0–7.9 and (b) magnitude >8.

**Figure 2.** Plot of outline rupture extent against calendar year of occurrence of earthquakes.
-400 km long fault (HFT), showing vertical separations of ~9–13 m, and ~18–26 m coseismic slip. This surface-rupture earthquake is assigned an age of ~AD 1500 on the basis of statistical average of C\(^14\) AMS ages obtained from different trench exposures. Another mega earthquake dated ~AD 1100, with surface displacement of ~17 m, lateral extent >240 km and magnitude MW 8.8 has been described along the HFT from the east-central Nepal.

The 26 December 2004 Sumatra–Andaman earthquake of moment magnitude 9.3 ruptured from northwest Sumatra to Andaman islands unilaterally for a length of ~1300 km, invoking predominantly thrust faulting at low (8°) angle with slip average about 13 m. The width of the rupture was 240 km at a depth of 40 km in Sumatra and 160–170 km wide at 30 km depth in Andaman. South of this rupture zone, there are records of several earthquakes during 1797 (M ~ 8.4), 1833 (M ~ 9), 1861 (M ~ 8.8) and 1907 (M ~ 7.8). In the northern segment of the 2004 rupture zone, Andaman Islands, large historical earthquakes of magnitude 7.2–7.7 have been reported during 1881, 1941, 1929, 1941, 1949 and 1955. Subsequent to the 2004 Sumatra–Andaman earthquake, the Nias earthquake of 28 March 2005 with moment magnitude 8.7 occurred to the south of the southern end of the 2004 event in the same region that was ruptured by the 1861 and 1907 events.

Review of the assigned magnitudes of past historical earthquakes, new knowledge gained through palaeoseismological and GPS studies and implications of the great Sumatra and Nias earthquakes have enhanced our understanding for better seismic hazard assessment in the Himalaya. Now we have the following facts on the seismicity of the Himalaya. (a) At least six large earthquakes of magnitude MW > 7.5 have occurred during the last 450 years in the Himalayan segment extending from Nepal westward to Pakistan. (b) Palaeoseismological studies have revealed two mega thrust-type earthquakes during ~AD 1500 and ~AD 1100 in Uttarakhand and Nepal SubHimalaya respectively. (c) Estimated potential slip determined on the basis of GPS-measured slip rate and magnitude of historical earthquakes suggests that the central seismic gap between the rupture zones of the 1905 Kanga and 1934 Bihar–Nepal earthquakes has accumulated elastic strain to generate more than one great earthquakes.

Two types of scenarios emerge from the above-described observations. Probability exists for the occurrence of a large earthquake, similar to that of the 8 October 2005 Muzaffarabad–Pakistan earthquake, with magnitude MW 7.5 to 7.8 and for a great to mega thrust-type of earthquake. Considering the distribution and lateral extent of the rupture zones of past historical earthquakes with assigned magnitude MW > 7.5, small size gaps of 80–100 km length may be recognized (Figure 2): (a) Chamba–Kishwar region between rupture zones of the 1905 Kangra and 1555 Kashmir earthquakes; (b) Eastern Himalachal region between the 1803 Garhwal and the 1905 Kangra earthquakes; (c) Western Nepal–eastern Kumaun region between the 1833 Nepal and the 1720 Kumaun earthquakes; (d) Eastern Himalayan region between the 1934 Bihar–Nepal and the 1950 eastern Assam great earthquakes has poor record of historical earthquakes, except the 1897, 1930 and 1943 events of magnitude >7 lying south of the Himalayan front.

There remains a high probability of having a large earthquake, similar to that of the 1803 or 1833 event or a great mega thrust-type earthquake observed in palaeoseismology trenches in the central seismic gap. A concerted and serious effort is needed from the Himalayan states, in particular Uttarakhand, for implementation of earthquake hazard mitigation and preparedness measures such as retrofitting of old buildings and infrastructure and introduction of building code for all new constructions. With new findings and data, it has also become necessary to revise the seismic zonation map of India.


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