Abstract

Himalaya, the world's highest and most spectacular mountain range is constantly rejuvenated by enormous tectonic forces generated from the ongoing collision of Indian and Eurasian continental plates. Crustal shortening imposed by this collision on the interseismically locked and seismically active megathrust system (Main Central Thrust (MCT), Main Boundary Thrust (MBT), Main Frontal Thrust (MFT), and Main Himalayan Thrust (MHT)) ultimately leads to strain accumulation, which is subsequently released in terms of earthquakes. The quiescence of significant earthquakes along different segments of the Himalayan arc in the last century may induce major to great earthquakes in the future. The April 25, 2015 Gorkha earthquake (M_w=7.8) was a dramatic reminder of such future incidence. The Himalayan arc has also experienced some devastating earthquakes in the past, namely the April 04, 1905 Kangra earthquake (M_w=7.8), January 15, 1934 Bihar-Nepal earthquake (M_w=8.4), August 15, 1950 Assam earthquake (M_w=8.6), and the October 08, 2005 Kashmir earthquake (M_w=7.6). Apart from these earthquakes, there have been evidences of at least hundreds of large to moderate events in the Himalayan orogen in the past hundred years. Yet, it appears that these earthquakes are inadequate to accommodate the $10-20$ mm/yr plate convergence (observed geodetically) that has gradually accumulated to more than a 9 m slip in the present day. This amount of total slip is sufficient to produce one or more massive great earthquakes in the Himalayan orogen. The high concentration of people and poor quality of building construction have further increased seismic vulnerability in the entire Himalayan arc and its adjacent regions.

In view of this, the current thesis addresses the present-day crustal deformation field along the Himalayan arc, through the analysis of GPS measurements. In the initial stage, a comprehensive surface velocity field and strain rate distribution are derived to visualize the crustal deformation pattern along the Himalayan arc. Next, the horizontal velocity vectors are inverted using a two-dimensional Bayesian splay-fault model to calculate the slip rate distribution of the Himalayan megathrust system, and the strain rates are utilized to compute the spatial distribution of earthquake potential along the Himalaya arc. In addition, a statistical investigation based on natural times is carried out to determine the current state of seismic hazard from large earthquakes in a dozen populous cities that belong to the Himalayan orogeny and nearby regions.

To derive the surface velocity field along the megathrust system of the Himalayan arc, a regional GPS network comprising three arc-normal transects (T1, T2, and T3) along with an arc-parallel transect (T4) was established in 2013-14. The network contains 08 permanent stations and 32 campaign-mode stations. The accrued data from the network were processed in the GAMIT-GLOBK suite of post-processing software. The surface velocity vectors (ITRF08 frame) are observed to vary from 37.62±0.14 mm/yr to 50.53±2.36 mm/yr. In order to provide a better visualization of the regional-scale deformation, all the surface velocities are rotated to align with an India-fixed reference frame. These horizontal velocities that vary from 0.45±2.58 mm/yr to 9.50±1.99 mm/yr exhibit a general southwest directed trend.

Further, in order to increase the spatial resolution of the regional velocity field, an updated set of 446 published horizontal velocities has been incorporated in a common reference frame (ITRF08) through a seven parameter Helmert transformation. The combined surface velocity field comprising 486 vectors vary from 37 mm/yr to 56 mm/yr with uncertainties lying in the range of $2-3$ mm/yr.

To characterize the crustal deformation pattern along the Himalayan arc, the surface velocity field is utilized to calculate the strain rate distributions. From the dilatational strain rates, it is observed that the compressional rates (-150 nstrain/yr to -200 nstrain/yr) are more dominant than the extensional rates (80 nstrain/yr to 90 nstrain/yr). This dominance of the compressional strain rate along the Himalayan arc is well justified by the collision boundary and the existing Himalayan megathrust system. Though the extensional strain distribution is not continuous along the Himalayan arc, some patches of it are evident along the Hindu-Kush, Pamir, and the Tibetan Plateau. On the other hand, the distribution of the maximum shear strain rates ($\sim$185 nstrain/yr) along the central and the northeast Himalaya reveal some evidences of strike-slip faulting in these regions.

To determine the spatial distribution of fault slip rate of the megathrust system, the surface velocity field is inverted along 15 arc-normal velocity profiles using a 2D Bayesian splay-fault inversion model. The modeling results suggest that the fault-slip rate of the MHT varies from 11.2±1.8 mm/yr to 17.0±1.8 mm/yr along the Himalayan arc at a depth of $\sim$20 km. The slip rate estimates of the MFT and the MBT suggest the progression of their locking behavior, starting from the northwest Himalaya, continuing to the central Himalaya, and further extending up to the northeast Himalaya. The slip rate of the MCT is observed to be higher along the northwest and the central Himalaya, whereas it is observed to be lesser along the northeast Himalaya. These slip rates of the megathrust system provide the evidence of a coupling zone along the Himalayan arc.

To obtain the spatial distribution of the earthquake potential along the Himalayan arc, the geodetic strain rates are translated into geodetic moment rates and compared with seismic moment rates derived from $\sim$900 years of seismicity data. The geodetic to seismic moment rate ratio, an indicator of stored strain energy, varies from below unity to more than 50 in different segments. The estimated geodetic moment rate ranges from 1.7×10^{18} Nm/yr to 10.2×10^{18} Nm/yr, whereas the seismic moment rate ranges from 3.7×10^{16} Nm/yr to 5.1×10^{19} Nm/yr. This variation between the geodetic and seismic moment rate corresponds to a moment deficit rate of $\sim1.15\times10^{17}$ Nm/yr to 7.97×10^{18} Nm/yr along various segments of the study region. The above moment deficit rate provides an equivalent earthquake potential of magnitude M_w $\sim5.7-8.2$ in different segments. Specifically, higher earthquake potential (M_w $\geq$8.0) corresponds to the segments in the central seismic gap and the northeast part of Himalaya, whereas the lower earthquake potential (M_w<7.0) corresponds to the segments encompassing the rupture areas of the recent large events.

To statistically address the current state of regional earthquake hazard at a dozen populous cities along the Himalayan subcontinent, an empirical data-driven technique, known as earthquake nowcasting, is utilized. In this method, the natural times, the cumulative number of intermittent small magnitude events between pairs of large earthquakes, are utilized to mark the evolution of the seismic process rather than the traditional clock or calender times. A number of reference probability distributions are fitted to the observed natural time counts to compute the Earthquake Potential Score (EPS) of a circular city region. The EPS scores for most of the cities along the Himalayan subcontinent are observed to lie in the range of 80% to 99%. Higher values of the nowcast scores indicate that these cities have reached to their rear end in the seismic cycle of large magnitude events.

Seismic hazard assessment using the above geodetic and statistical methods are all related to the concept of elastic rebound. While the geodetic approach has provided a long-term prospective of strain accumulation, the proposed nowcasting approach has determined the current progression of earthquake cycle in several target localities. As a consequence, a combination of these two methods have provided a snapshot of high seismic hazard areas along the Himalayan arc.

In summary, the present study has significantly improved our understanding of the ongoing crustal deformation and subsequent seismic hazard analysis in terms of the updated surface velocity field, strain rate patterns, fault kinematics of the megathrust system, and the spatial distribution of earthquake potential along the Himalayan arc. The findings

of the present investigation may further facilitate in developing a three-dimensional fault model, characterizing the possible influence of subducting ridges on Himalayan tectonics, and casualty estimates in repeat Himalayan earthquakes, leading to an efficient seismic risk reduction strategy in the densely populated study region.