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Himalayan Landslides–Causes and Evolution

**Sandeep Singh, Anand Joshi, Anamika Sahu, R. Arun Prasath,
Saurabh Sharma, and Chandra Shekhar Dwivedi**

Abstract The Himalayas has been characterized by many superlatives, viz. youngest mountain chain, the highest peak, home of severe earthquakes, and the highest cases of landslides. The landslides are inevitable due to the presence of fragile rocks, the presence of major tectonic boundaries, and the activities along with them due to the northward movement of the Indian Plate; Earthquakes of high magnitude. Both geological and historical records indicate landslides devastating nature, causing a large scale of destruction and losses. There has been an emphasis on monitoring landslides with various modern techniques for systematic studies to highlight the landslide's extent and effect in suggesting proper remedial measures.

Keywords Himalayas · Landslides · Earthquakes · Monitoring of landslides

1 Introduction

Landslides are considered one of the most significant natural hazards worldwide. The total number of fatal landslides in the world indicates that nearly 75% of total occur in Asian countries, out of which substantial numbers have occurred in Himalayas (Froude and Petley 2018). The Himalayas regions belong to moderate to very high global hotspot landslide hazard zonation with a high Mortality rate for expected annual mortality risk of landslides worldwide (Nadim et al. 2006; Yang et al. 2015). The Himalayas represent a rugged topography zone (Fig. 1), high-intensity rainfall, and the rain shadow zone, along with the high magnitude of the earthquake (Fig. 2).

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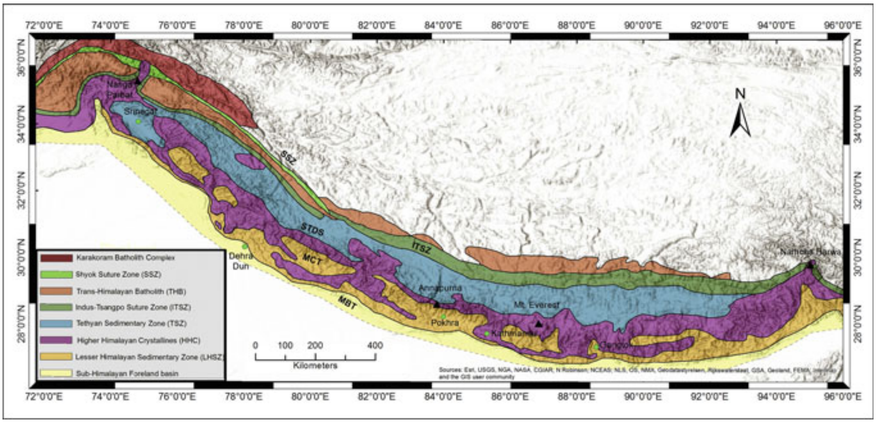

Fig. 1 Simplified regional geological framework of the Himalayas in Plate tectonic framework. Higher Himalayan Crystallines (HHC) have been redefined by few workers as Great Himalayan Sequence (GHS) Abbreviations: SSZ-Shyok Suture Zone. ITSZ-Indus Tsangpo Suture Zone. THSZ/STDS-Trans Himadri Shear Zone/South Tibetan Detachment System (STDS). MCT-Main Central Thrust. MBT-Main Boundary Thrust. After Singh (2019)

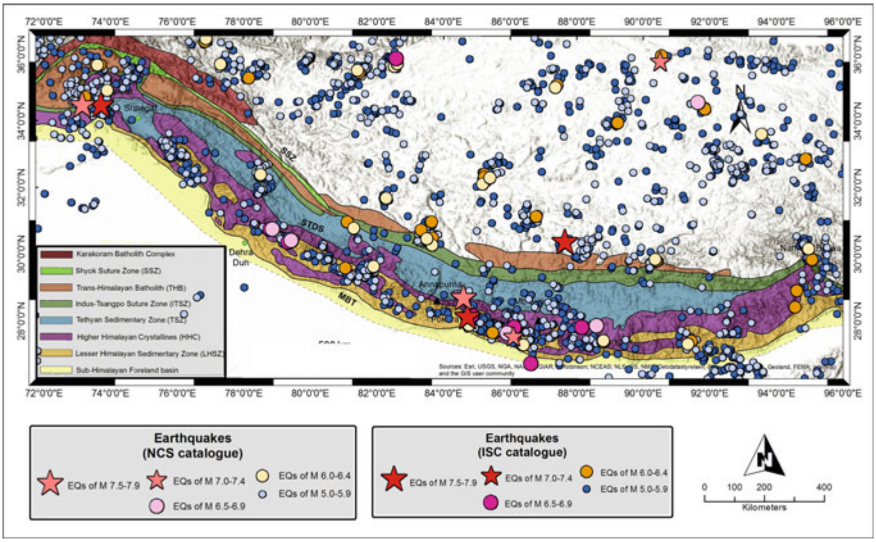

Fig. 2 Location of earthquakes and magnitude based on ISC-catalog (ISC 2020; last accessed: 29th Dec 2020) and NCS-catalog (NCS 2020; last accessed: 29th Dec 2020) in the Himalayas. The base map is after Singh (2019)

Landslides, debris flow, soil erosions, and other mass wasting processes characterize the Himalayas. The erosions have led to the formation of Himalayan Foreland basins, which have been described by the Sub- and Lesser Himalayan zone and the Indo-Gangetic Plain (Singh and Singh 2020).

The reason for substantial numbers of landslides in the Himalayas is the presence of vulnerable rocks, steep slopes, and building up of strain due to the northward movement of the Indian Plate beneath the Asian Plate (Singh 2019 and references therein). The continuous northward movement of the Indian Plate and its collision with the Eurasian Plate is causing earthquakes and other neo-tectonic activities in this part of the Indian subcontinent. Weak, incompetent rocks are more likely to cause landslides than strong, competent rocks; similarly, the general steeper slope has a greater chance of land sliding than the gentle slope. The frequency of landslide increases many folds once the equilibrium is disturbed in the highly undulating mountainous terrain.

During the monsoon (summer and winter), landslides and related natural disasters affect human life in the Himalayan region. Most of the human settlements are situated in the paleo-landslide zone due to the presence of fertile soils. Rainfall raises pore-water pressure in slope materials, which can trigger landslides. Earthquakes, increased overburden, change in slope gradient, mining, hill cutting, constructions, human activities, etc., can also trigger landslides.

Dikshit et al. (2020) analyzed the landslide studies based on the web of science across the states in the Indian Himalayan region. They worked out that the studies are quite biased toward the Uttrakhand region consisting of 51%, followed by West Bengal (15%), Himachal Pradesh (13%), Sikkim (10%), Jammu and Kashmir (5%), Arunachal Pradesh (3%), Mizoram (2%), Manipur (1%). It also indicates that northeastern Himalaya has very few to almost none studies.

2 Type of Landslides

Landslides often occur on hillslopes, which pull the soil and rock downslope; this only occurs when the developed stress in the rock mass exceeds the strength of the hill slope material (Hyndman and Hyndman 2009). It shows significant variability in terms of its typology along with kinematics and geometric variabilities. The landslide classification is mainly based on the type of material involved along with the type of movement along any slope (Cruden and Varnes 1996). There could be more than one type of movement and the cause of triggering the landslide. Varnes (1978) made the first attempt to classify the landslide and has been widely used and even adopted by Landslide Committee, Highway Research Board, Washington (Thakur 1996). They recognized the movement of soil, rock, debris, or earth downslope either by fall, topple, slide, spread, or flow.

3 Himalayas and Lithotectonic Units

The Himalayas results from the continent–continent collision between the Indian Plate and the Asian Plate no later than 57 Ma (Leech et al. 2005, 2007). It forms a fascinating, spectacular, modified sculptured landscape between two syntaxial bends knows as Namche Barua (7782 m) in the east and Nanga Parbat (8125 m) in the west, where the range takes a sharp turn toward the south (Figs. 1 and 2—Singh 2019 and references therein). The collision resulted in the Himalayas formation with extreme and intense crustal shortening and upliftment of the world's highest and youngest mountain chain.

From north to south, the Himalayas can be divided into five lithotectonic units with distinct characters (also see Jain et al. 2002; Yin 2006) exposed along the E-W strike of the Himalayan orogeny, they are:

1. The Tethyan Sedimentary Zone (TSZ)
2. The Higher Himalayan Crystallines (HHC)
3. The Lesser Himalayan Sedimentary Zone (LHSZ)
4. The Sub-Himalayan Foreland Basin (SHFB)
5. The Indo-Gangetic Plain (IGP).

The **Tethyan Sedimentary Zone (TSZ)** is the northernmost part of the Indian Plate lithotectonic units of the Himalayas. It consists of mildly deformed to almost undeformed sedimentary sequence very prone to landslides, but due to rain shadow zone and less habitation, there is less threat for landslides. The South Tibetan Detachment System (STDS) separates these rocks in the south from Higher Himalayan Crystallines (HHC). The rocks are composed of shale, limestone, and sandstone, ranging from Neoproterozoic to Eocene.

The **Higher Himalayan Crystallines (HHC)** is composed of crystalline rocks and are divided into two thrust sheets; the lower portion between Main Central Thrust (MCT) and the Vaikrita Thrust (VT) called as Munsiari Group of rocks and the upper part between Vaikrita Thrust (VT) and STDS known as Vaikrita Group of rocks. Both these packages form 15 to 20 km thick high-grade metamorphic rocks all along Himalayan orogeny with varying thickness. The rocks are made up of schist, gneisses, quartzite, marble, migmatites, and granite bodies of various ages (see Singh and Jain 2003; Singh 2020).

The **Lesser Himalayan Sedimentary Zone (LHSZ)** is exposed in two zones and can be classified as Inner Lesser Himalayan Zone (ILH), occurring in window structure, and Outer Lesser Himalayan Zone (OLH) bounded between Main Boundary Thrust (MBT) in the south and Main Central thrust (MCT) in the north which separates them from HHC. The rocks are mostly low-grade sedimentary sequences and made up of mostly unfossiliferous shale, sandstone, limestone, dolomite, slate, phyllite, schist, and quartzite.

The **Sub-Himalayan Foreland Basin (SHFB),** also known as **Shiwalik Belt,** is exposed in the south of LHSZ between Main Boundary Thrust (MBT) in the north and Himalayan Frontal Thrust (HFT) in the south. The rocks are consisting of mudstone, siltstone, shale, sandstone, and conglomerate. The rocks of this region are prone to landslide because of the loose nature of rocks and monsoonal activities.

The **Indo-Gangetic Plain (IGP)** is a compressional tectonics product between the Early Miocene and Middle Miocene and attained present-day configuration (Singh 1996). The GAP accumulated eroded sediments from the various Himalayas and Peninsular India lithologies during Cenozoic time (Shukla et al. 2012). GAP geometry is controlled by flexural subsidence related to the foreland basin character of the Himalayas having depo-center close to the front (Mungier and Huyghe 2006). Geophysical data suggest transverse ridges and saddles (e.g., Delhi Haridwar Ridge; Dholpur Saddle; Faizabad Ridge; Meja Saddle). The northern depressions (e.g., the Sharda Depression; the Bahraich Depression; the Gandak Depression—Srinivas et al. 2013; Mangalik et al. 2015 and references therein) having graben-like structures that go as deep as ~4 km (Manglik et al. 2015; Singh and Singh 2020).

4 Causes of Landslides

Rock type and its effects: Each rock has a distinct character in terms of chemistry, mineralogy, and textural attributes. Rocks' primary character is a significant factor in determining the strength of rocks. Simultaneously, secondary discontinuities and the surface layer of weathered material are the main factors for the landslide occurrences in any area. Secondary discontinuities are faults, joints, and bedding planes. Rock failure causing landslides mainly depends on the geometry and mechanical properties of secondary discontinuities with slope geometry.

Tectonic Boundaries and their effects: In Himalayas, major tectonic boundaries like South Tibetan Detachment System (STDS), Main Central Thrust (MCT), Main Boundary Thrust (MBT), Himalayan Frontal Thrust (HFT) and their associated splays are playing a critical role in the stress accommodation along the whole of the orogeny. The movements along these major tectonic boundaries and their splays are responsible for generating earthquakes in the region. The distances from these major tectonic boundaries affect the severity of landslides.

Earthquakes and their effects: Strong ground motion associated with earthquakes weaken slope material causing co-seismic landslides. The landslides contribute about 20–25% of the losses due to earthquakes and are known as earthquake-triggered landslides. The probability that landslides will occur in landslide-prone areas generally increases if an earthquake strikes that region. An earthquake occurs along a plane known as the fault plane. Earthquakes happen when two rock blocks slip past each other along the fault, causing stress to buildup. When the stress exceeds the moving blocks' frictional energy, earthquakes occur, and seismic waves are formed. The spot where the rock breaks in the subsurface and is the nucleation point of the released energy is the hypocentre.

There are many accompanying effects with large earthquakes, viz. landslides, tsunami, conflagrations, etc., (Lowrie 2007). In the mountainous region, the earthquake's associated hazard triggers landslide, which can cause devastation even in the areas far away from the epicenter. Highland and Bobrowsky (2008) defined landslide as the downslope movement of rock, debris, or soil material under the impact of gravity. The downslope movement of rock or soil can be either rotational or translational depending on the surface of rupture. The well-designed structures and buildings are affected because of the local soil response during a landslide. The Indian Himalayas lies in the seismic zone V and IV, making it more vulnerable to larger earthquakes (Indian Standard, I.S. 2002). The ground-shaking due to earthquakes cause fluidization and liquefaction, causing landslides along the slopes. Also, the ground-shaking loosens the rock material, which causes rockfall and rock topple. The minimum earthquake magnitude required to generate a landslide is M_L ~ 4 (Keefer 1984).

There are numerous examples of moderate to great earthquakes in the Himalayas; which are Assam (1897), Kangra (1905), Bihar-Nepal (1934), Shillong (1950), Bihar-Nepal (1988), Uttarkashi (1991), Chamoli (1999), Kashmir (2005), Central Nepal (2015), etc. These great earthquakes are responsible for the disaster and casualties due to the slope failures initiated by these earthquakes (Prakash 2013; Prasath et al. 2019 and references therein). The landslides that occurred due to these earthquakes have been studied to understand the conditions like tectonic, morphological, lithological, etc., which play a vital role in the landslides' occurrences. The possible earthquakes of high peak ground acceleration 0.4 and 0.25 g with a return period of 500 years increase the landslide activities on hillslopes.

Slope stability is the resistance offered by any rock slope or inclined soil to the failure by sliding or collapsing. The slope stability analysis is mainly based on traditional methods, which can be grouped as kinematic analysis, limit equilibrium analysis, and rockfall simulators (Eberhardt 2003). Limit equilibrium methods examine the equilibrium of a landmass tending to slide on the slope under gravity influence. The assumption in these methods is that the shear strengths of the material along the surface under failure is regulated by linear or non-linear relationships between shear strength and the normal stress on the surface under failure (EM 1110-2-1902). The Mohr–Coulomb criterion depicted in Fig. 3 presumes that a yield occurs when the shear stress acting on a surface reaches up to a linearly dependent on the normal stress in the same plane. The straight line touching these Mohr's circles is known as the yield line (Hibbitt 2004).

Paleo-landslides and their effects: Pre-historic landslides are very common in the Himalayas. The human settlements are concentrated within the paleo-landslide zone because of the presence of soil and fertile land. They are the vulnerable center of landslides and can be identified by landform and other geomorphic features.

In the Himalayas, paleo-landslide are often associated with the nick point that is very prominent on the river's longitudinal profile and indicates rejuvenation in the past. A narrow valley characterizes these nick points with a broad valley in the upstream direction and the development of lacustrine deposits in the broad valley due to the filling of paleo-lakes materials (Singh and Jain 2007). The lacustrine deposits also record sesimites (paleoseismic deformational structures) indicating landslides' development due to seismic activities in the nearby area (Singh and Jain 2007 and references therein).

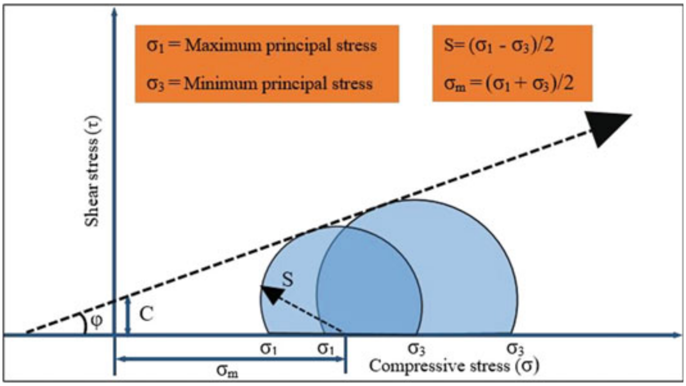

Fig. 3 Linear Mohr–Coulomb failure criterion (Su et al. 2016)

Anthropogenic effects: The anthropogenic intervention aggravated the situation of pre-existing conditions of landslide occurrences. It includes modification/alteration of (i) topography; (ii) water circulation both underground and surface; (iii) land use. These effects generally incorporate deforestation, urbanization, slope support removal during road cutting, mining with blasting, and heavy traffic movement.

5 Monitoring of Landslides

The best possible result from monitoring can be achieved only by a proper understanding of the landslide in geology, geophysics, geomorphology, geohydrology, surveying (aerial extent), and civil engineering aspects. Different methodologies for assessing landslide are influenced by the scale of analysis, input data availability, and required details. For landslide study, it is essential to prepare several thematic maps. The choice includes geological informations in the forms of lithology, structures (foliations, fold, fault, joints, shear zone, etc.), slope angles, relative relief, hydrological details, land use, and land cover. Once they are prepared by overlaying these thematic maps, vulnerable areas can be identified. For generating these maps, various techniques are being used to achieve near realistic pictures, which is useful for future planning.

Applications of geodetic techniques, information, and geospatial technology such as remote sensing and geographic information system (GIS) help monitor the landslides. They include (a) landslide susceptible analysis (Probabilistic approach and/or Deterministic approach)—which include (i) Quantitative method (direct mapping and indirect mapping), (ii) Quantitative method/Data-driven method (Bivariate statistics, Multivariate statistics, Artificial neural network); (b) Runout modeling—it includes volume-based model and dynamic model; (c) landslide monitoring and early warning.

Photogrammetric techniques: Photogrammetry techniques involves the interpretation of aerial photographs (orthophotos) of multi-years. It reveals quantitative information on surface characteristics and indicates geomorphological changes and position size and shape of the landslides (Linder 2009).

Remote Sensing or satellite techniques with space-derived information: (a) Synthetic Aperture Radar (SAR) images, (b) Interferometric Synthetic Aperture Radar (InSAR). An interferometric difference of 2 phase images of the same area at a different time to detect ground motion. Combining many interferograms produce a mean velocity map in which the color shows the ground's speed and indicates sudden movement, if there is any.

Ground-Based Conventional Surveying techniques: (a) Triangular leveling (b) Monitoring by total station. Different surveying techniques are instrumental in the monitoring of landslides, which can include single point positioning (SPP), precise point positioning (PPP) with pseudo kinematic, and real-time kinetic strategies (Tiwari et al. 2018 and references therein).

GPS techniques: The Global Positioning System (GPS) determines the precise determination of point coordinates. Compared to classical surveying, it allows faster and similar accuracy of data acquisition for landslide studies. It can have either the Fast Static (FS) method or Real-Time Kinematic (RTK) techniques (Gilli et al. 2000).

Geotechnical techniques: Sensor-based monitoring (a) Extensiometer: (measures the axial displacement between several reference points in the same measurement axis. They can be installed in boreholes or surfaces. There is also a wire extensometer, typically measuring baseline up to 80 m in length with an accuracy of ±0.3 mm per 30 m. The accuracy gets also affected by temperature. (b) Inclinometer: These are instruments installed in boreholes drilled within the landslide zones. They measure the curvature of the initially straight borehole casing. (c) Piezometer: It measures the pore-water pressure of the landslide zone. Threshold values can be defined to warn. (d) strain meter (e) pressure cell (f) Tiltmeter (g) crack meter (h) geophones: it measures the vibration associated with movement. They can detect landslides based on frequency composition, amplitude, and duration of the vibration signal.

6 Conclusions

- Apart from catastrophic landslides, many small-scale slope failures cause the loss of productive land, which goes unnoticed.
- There is a various cause of landslide occurrence in the Himalayas. It is important to analyze different triggering mechanisms to characterize individual landslides.
- A rapid rise of anthropogenic activities also contributes to the triggering of landslides in the Himalayas.
- It is, therefore, require to undertake systematic studies of landslides, which is still in their infancy.

- It is necessary to prepare zoning maps of landslide-prone areas through geological and geo-technical studies.
- Monitoring of landslides' activities with modern techniques is vital for future planning along with remedial measures.
- The remedial measures involve reforestation, proper drainage, erecting protection structures, and reducing slope angles.

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