Earthquake Related Landslides in the Indian Himalaya: Experiences from the Past and Implications for the Future

Surya Parkash

Abstract

Most parts of the Indian Himalaya fall in seismic zone V and IV, indicating a high degree of susceptibility to earthquakes. Although numerous studies on earthquake risk assessment have been done by different researchers yet very few of these studies and reports have focused on landslides related to earthquakes. It has been observed globally that many casualties during an earthquake in a hilly terrain are attributed to the incidences of landslides triggered by the earthquake and the response actions are also hurdled by the rockfalls/landslides along the highways. Field observations have indicated that such landslides are often associated with earthquakes of magnitude 4 or more. About 20–25 % losses during earthquakes in hilly terrains have been attributed to landslides. The earthquake triggered landslides have affected even the structures and buildings which were well constructed but adversely located in the ground. However, a perusal of seismic zonation studies indicate that landslides have not received due attention. Similarly most of the landslides hazard zonation studies do not consider the impacts of earthquakes in generating numerous and large landslides. Hence, the present paper emphasizes the significance of earthquake related landslides in the hilly terrains through experiences from the past incidences of landslides during earthquakes along with their impact and proposes its consideration in future earthquake risk management programmes as well as in landslides hazard zonation studies for effective risk reduction strategies. The significant earthquakes that affected the Himalayan terrain include Assam (1897), Kangra (1905), Bihar-Nepal (1934), Shillong (1950), Bihar-Nepal (1988), Uttarkashi (1991), Chamoli (1999), Kashmir (2005) etc., that caused heavy damages/losses as well as casualties which were found partly related to the ground and slope failures during these earthquakes. A study of landslides associated with earthquakes has lead to identification of morphological, lithological, tectonic, hydrological and landuse conditions that govern the occurrence of such landslides. For example, most of earthquake triggered landslides/rockfalls happened on convex slopes whereas rain-induced landslides are more common on concave slopes. The concentration of landslides and their size has also been found proportional to the magnitude of the earthquake to some extent. An attempt has also been made to differentiate freshly triggered and reactivated co-seismic landslides in earthquake affected areas as well as post-seismic landslides.

Keywords

Earthquake • Landslide • Himalaya • Risk

S. Parkash (✉)
Geohazards Division, National Institute of Disaster Management, 5B, I.P. Estate, M.G. Road, New Delhi 110002, India
e-mail: suryanidm@gmail.com

C. Margottini et al. (eds.), *Landslide Science and Practice*, Vol. 5,
DOI 10.1007/978-3-642-31427-8_42, © Springer-Verlag Berlin Heidelberg 2013

Introduction

Globally several earthquakes took place in different hilly regions like Bam earthquake (26 December 2003, Ms-6.5), Wenchuan earthquake (12 May 2008, Ms-8.0), Pak earthquake (8 October 2005, Mw-7.6), Elazig earthquake (8 March 2010, Mw-6.1) and resulted in heavy damages/losses due to landslides related to these earthquakes. Similarly the Indian territory has also faced significant earthquakes like Shillong (12 June 1897, M-8.7), Kangra (4 April1905, M-8.0), Bihar-Nepal (15 January 1934, M-8.3), Assam (15 August 1950, M-8.6), Bihar-Nepal (20 August 1988, M-6.6), Uttarkashi (20 October 1991, M-6.4), Chamoli (29 March 1999, M-6.6), Bhuj (26 January 2001, M-7.7), Indian Ocean (26 December 2004, M-9.3), Kashmir (8 October 2005, M-7.6), Sikkim (14 February 2006, M-5.7) etc., that caused heavy damages/losses as well as casualties which were found partly related to the ground and slope failures during the earthquakes.

The paper will briefly discuss the broad topography, seismicity and landslides along with the observations made by former researchers in the study area and also relate them with other parts of the world. Finally, it will try to assess the impacts of earthquake related landslides and implication in future strategies for earthquake risk reduction.

Topography, Seismicity and Landslides in Himalaya

Topography is one of the most important parameter in earthquake related landslides in the hilly terrains. Therefore, it is desirable to briefly discuss about the topography of the area under study. The Indian Himalaya constitutes large variations in relief from low lying valleys (close to mean sea level) to high altitude mountainous areas (ranging >20,000 ft) as well as plateau regions. Thus, the likelihood of earthquake related landslides are very high. Further the region receives heavy rainfall (sometime >5,000 mm per year) during the monsoons and also due to orographic phenomenon resulting into cloudburst/thunderstorms. Intense & frequent rainfalls, particularly during the monsoons, have a marked impact on the spatial distribution of landslides. The antecedent precipitation before the earthquake events also makes the slopes more susceptible to landsliding. Similarly post event precipitation results into seepage of water into the slopes through the fissures and cracks developed during the earthquake causing post-earthquake landslides.

Seismically, the continuous tectonic activities have produced several catastrophic events in the past, as indicated through the seismic zonation map of India, where this area falls in seismic zone V and IV. It indicates that earthquakes of seismic intensity VIII or IX are possible in this region; with peak ground acceleration (PGA) as high as 0.4 g and 0.25 g, respectively for a return period of 500 years. It is quite possible that these levels of accelerations can generate landslides in hillslopes. However, large epicentral distances where landslides have been reported seem to be controlled by slope susceptibility rather than seismic load as can be seen by low values of minimum accelerations related to farthest landslides.

Landslides – Rock falls have commonly occurred in road and river cut slopes usually causing traffic disruption whereas translational landslides are commonly found along discontinuities dipping out of the slope face. These landslides are sometimes responsible for damming river or its channels and at times breaching of the dams/reservoirs, resulting in flash floods on downstream side. Lateral spreads are commonly found in sands or silts that liquefy due to building of dynamic pore water pressure. These slides initiates in very gentle slopes in the alluvial, deltaic or lacustrine deposits.

Review of Literature

A review of literature has been made to find out the major observations and suggestions from the past earthquake in the Indian Himalaya. The following section describes these earthquake events with particular reference to landslides.

During the Shillong earthquake (12 June 1897, M-8.7), landslips were caused on an enormous scale and deserved a special notice, both as to their origin and distribution. The landslips were produced by displacement of weathered surface layer that seldom extended deep into the hill. Besides these, the high sandstone scarps of the southern edge of Khasi and Garo Hills exhibited landslides due to throwing off of a greater or less width of solid sandstone on a large scale. In case of both these forms of landslips, the part of the hill which is left standing is always scarred with deep fissures, extending more or less parallel to the free face of the fall, and due to partial detachment of the material between them and the edge of the actual slip.

Bihar-Nepal Earthquake (15 January 1934, M-8.3): Landslides occurred in the mountain areas near Kathmandu, Udaipur, Garhi and in eastern Nepal. Most of these landslides in Kathmandu area were falls in metamorphic and crystalline rocks (phyllites, quartzites, granite-pegmatites) that formed part of the ridge in this valley. The hillsides in Udaipur Garhi were widely scarred with rock fall in gneisses and schists where vegetation was scanty. The falls were observed in the Siwalik Sandstones near Muksar which blocked the local channel and created lakes. Two of these lakes emptied after several weeks. The larger of the remaining lakes was about 600 ft long with a probable maximum depth of 25 ft. In Dharan, Dhankuta, one landslide caused 30 deaths while the other one resulted in 13 deaths.

These landslides weighing thousands of tons, occurred in gneisses, mica-schists and shattered quartzites. In Taplejung, two large pre-existing landslides were also reactivated. One of these landslides originated in 1927 and the other started in 1924. However, the Happy Valley Landslip Area did not move, evidently due to precautions taken in the previous years proved effective.

Bihar-Nepal earthquake (20 August 1988, M-6.6): The report of the Geological Survey of India on Bihar – Nepal Earthquake (20 August 1988) indicates that while many of the slides were attributed to the combined effects of earthquake and rainfall, the rockslides at Tindharia in Darjeeling district have directly been triggered by the earthquake. At Bansoi in North Sikkim, major landslides have occurred as a result of earthquake vibrations. However, as the ground vibrations did not penetrate deep into the slope, landslides on extra-ordinary scale did not occur.

In addition to the review of literature, the author would like to mention about some experiences gained from Uttarkashi earthquake (20 October 1991, M-6.4), Chamoli earthquake (29 March 1999, M-6.6) and Elazig earthquake (8 March 2010, M-6.0). The author observed an intimate relationship between seismic vibrations and landslides that either directly generated co-seismic landslides or destabilized the slope mass through volume expansion, fissures, cracks and deformations which subsequently caused post-seismic landslides. The size and distribution of these landslides appeared to be a function of the earthquake magnitude, depth, epicentral distance, and location on the fault plane. However, the occurrence of these landslides was subjected to various factors controlling landslide susceptibility, climatic and anthropogenic interventions. Sometimes these landslides appear to be very deceptive in nature making it difficult to identify them in the field.

Mechanism of Failure for Earthquake Related Landslides

Basically two major types of failures can be distinguished for earthquake related landslides. These are (1) Co-seismic landslides which occur during the earthquake event. These can be freshly triggered landslides or re-activated existing/ ancient landslides. (2) Post-seismic landslides which occur after the earthquake event has passed but owes its origin to fissures, cracks, deformations induced by the earthquake event. The following section discusses the mechanism of failures for co-seismic and post-seismic landslides.

Co-seismic Landslides

According to Oldham (1899), when the rock of hill is set into elastic vibration by the earthquake wave, the superficial portion will, at one period or the other of the shock, be set in movement outwards, and this movement will be communicated to the soil cap. In the next semi-phase of the wave, the movement of the surface of the rock will be inwards, but the inertia of the overlying soil cap will prevent this following at once, and the effect will be a more or less complete reduction of the pressure of the soil cap on the rock. This reduction of pressure means a reduction of the friction, which alone prevents the soil cap from sliding down the hill, and so a landslip is formed where the reduction of resistance and the slope of the hill are sufficient to allow it.

In cases, where the adhesion of the subsoil to the underlying rock is great, where its thickness is small, or where the violence of the shock is not great enough, the slippage of the surface layer does not amount to a landslip, and in these cases the hillsides are found to be scarred with fissures. At the other extreme, the momentum imparted to the surface layer may be so great that an actual outward pull is set up, sufficient to overcome the resistance of both gravity and adhesion of the subsoil to the rock, and then we have not merely a landslide but the whole face of hill shot bodily off. The conditions that allow this appear to be rare, but they certainly did occur in some of the high scarps of the Khasi and Garo Hills.

In case of both these forms of landslips, the part of the hill which is left standing is always scarred with deep fissures, extending more or less parallel to the free face of the fall, and due to a partial detachment of the material between them and the edge of the actual slip.

It is only under very exceptional circumstances that a wave of low velocity, or acceleration, of wave particle could give rise to landslips. Given a sufficiently violent earthquake, the other factor that comes into play is the natural tendency of the hill to slip. This obviously varies with the slope; a gentle slope being much less liable to slip than a steep one and the nearer the slope reaches that critical angle at which the soil cap should slip away at its own accord, the less the impulse required to set it in motion. During earthquakes, slope materials behave in an undrained manner because excess pore pressures induced by dynamic deformation of the soil column can not dissipate during the brief duration of seismic shaking.

There is, however, another factor which appears to be of almost equal importance with the angle of the slope that is the height from base to crest. Steep slopes and scarps of low height, had remained uninjured, while gentle slopes that formed part of a hill rising to several hundred feet had been scarred with landslips. Where the hills are high and cut by deep valleys, landslips are common. But where the height of the hills above the valleys is much smaller, landslips are almost unknown though the earthquake was on the average equally severe.

The explanation of the connection between the height of the slope and the degree to which they have been scarred by landslips is doubtless the greater swing which was imparted to higher hills. This is due to the fact that an equal angular motion would result in greater linear movement at the top of a high hill than of a low one. But mainly it is due to the greater elastic play of the high hill, especially when steep sided; just as the end of a long switch jerked to and fro describes a larger area than that of a short one.

There is yet another factor in generating landslips, i.e. mineral constitution of the hill. When the hill is composed of crystalline rocks, the surface layer of disintegrated and weathered material is either thin or it passes down into the unweathered rock in a gradual manner. In the former case, the thin skin may not acquire sufficient momentum to cause it to be detached from the underlying rock. In the latter, the gradual increase in the cohesion of the surface layer, adhesion to the underlying rock is proportionate to the increase of strain applied, and the surface layer will be much less liable to come away than if there was a more or less well defined plane of weakness.

In the case of sedimentary rocks, the boundary between the weathered soil cap and the underlying rock is generally more abrupt and the surface layer readily separates from the rock below. These rocks (sandstones) have much lower cohesive strength than the crystallines and metamorphic rocks and when such rocks form high scarps, portions of solid rock itself may be thrown off.

Thus, besides the energy of earthquake waves, the production of landslips is controlled by the petrological composition of the hill, slope angle and height of the hill including size and form. Attributing the whole effects to only one of the operating causes may not be appropriate.

It is difficult to detect any relation between the size and frequency of the landslips and the direction of the slope, direction of the travel of earthquake wave as the geological and orographical conditions control the highest and steepest slopes.

Post-seismic Landslides

The observations on landslides that occurred after some time of the main earthquake has provided the following information.

A part of the effects noticed was due to the action of heavy rains following the earthquake and partly to the aftershocks of the main earthquake. Many of these were themselves violent enough to cause landslips, the more so as many hillsides, which had not come down in the main shock, had been badly shattered and weakened, and were more easily broken down than otherwise would have been the case.

The heavy rains which followed the earthquake probably had even a greater effect than the aftershocks in bringing down the hill sides, which had been fissured and weakened by the earthquake. It was not found possible to distinguish the direct effects of earthquake from its indirect effects or those of after-shocks. However, the larger number of landslides occurred during the earthquake and the subsequent additions to the size and number were only a fraction of what could be seen immediately after the main shock.

Bhandari (2006) laid down the following observations for cases of earthquake induced landslides.

- No slope mass with a static factor of safety of 1.7 or greater has failed in an earthquake, no matter how large in magnitude
- Steep sided bedrock ridges are generally subjected to more intense level of ground shaking than adjacent valleys are in the near field area, close to the source of shaking. An exception of this may come because of the amplification of the strong motion due to alluvium cover on the valley bottom.
- The response of a large ancient landslide to seismic forces is significantly modulated by number of strong motion cycles (duration of shaking) rather than by short-lived peak ground acceleration. With each cycle, more and more of seismic energy gets trapped into the body of the slope, thereby robbing of its elastic response, eventually causing local slippages, or a full fledged landslide.
- When a slope fails as a rigid body, the acceleration is assumed to be constant over the entire slope, and usually it refers to the horizontal component of the slope surface acceleration.
- Ground surface acceleration alone is a poor measure of the effect of shaking on slope stability, intensity even more so. Ground velocity, the experiences during the occurrence of past large magnitude earthquakes, and the duration of the shaking are considered to be better indicators of landslide susceptibility under seismic conditions.
- Ground cracks generated by earthquakes serve as conduits for rain water and become source for weak ground in the long run.
- The limiting threshold for an earthquake induced landslide is earthquakes of magnitude 4 or more on the Richter scale.
- Area within which landsliding is generated tend to increase with the magnitude of earthquake shock, from $<100\ km^2$ at magnitude 4, rising to about $500{,}000\ km^2$ at magnitude 9.2 (Keefer 1984). The influence zone gets modified by external factors such as ridges, convex slopes and escarpments.

Observations Made by Other Researchers

- Where landslides can be triggered by typhoons (tropical cyclones) and earthquakes, a rain-induced model is insufficient because it provides only a partial explanation of landslide occurrence and overlooks the potential effect of earthquake on typhoon triggered landslides (Chang et al. 2007). Thus, there is a need to develop models for earthquake induced landslides as well as typhoon induced landslides. Typhoon triggered landslides tend to be near stream channels and earthquake triggered landslides were more likely to be near ridge lines.

- Most of the loess landslides triggered by the Haiyuan earthquake (China 1920) occurred on concave slopes gentler than 15° with long run-out distance, showing very small equivalent friction angle (Zhang and Wang 2007)
- Landslide moving directions showed preferred orientations normal to the fault ruptures, indicating the effect of the directivity of the seismic wave (Chigira et al. 2010). Slow and fast moving landslides as well as factors affecting their occurrence are also very important for estimation of landslide impacts.
- ANOVA (Analysis of Variance) technique has been used to determine how the occurrence of landslides correlates with distance from the earthquake source, slope steepness, and rock types. The landslide concentration (defined as the number of landslide sources per unit area) has a strong inverse correlation with distance from the earthquake source and a strong positive correlation with slope steepness. The landslide concentration differs substantially among the various geologic units in the area. The difference correlated to some degree with differences in lithology and degree of induration, but this correlation is less clear, suggesting a more complex relationship between landslide occurrence and rock properties (Keefer 2000)
- The number of landslides is disproportionate for the size of the earthquake. There are also important differences in the characteristic type of landslides in different geological terrains. For example, soil falls and slides in steep slopes in volcanic soils predominated in Guatemala and El Salvador, whereas extensive translational slides in lateritic soils on large slopes are the principal hazards in Costa Rica and Panama (Bommer and Rodriguez 2002).
- Rodriguez (2006) studied the relationship between earthquake magnitude and landslide characteristics in Colombia. It was found that residual and volcanic soils are more susceptible to landslides by earthquakes. The influence of precedent climatic conditions was observed in reducing the seismic load required to induce landslides.
- Over 10,000 landslides were triggered by the September 21, 1999 Chi-Chi earthquake. The most abundant landslides were shallow, disaggregated rock and soil slides. Landslides occurred primarily in Tertiary sedimentary rocks, which are well known for their susceptibility to landsliding in many parts of the world. Landslide concentration values diminish beyond epicentral distance of 40 and 70 km from the epicenter and the surface projection of the fault plane respectively (Khazai and Sitar 2004).
- In the epicentral areas of major recent earthquakes, landslide density scales with PGA. Topographic site effects on seismic waves are known to cause important gradients in ground acceleration in individual mountain areas. Earthquake triggered landslides clustered ner ridge crests, where the susceptibility to landsliding was greatest. Secondary landslide clusters were found in colluvial slope toes (Meunier et al. 2008).
- Nepop and Agatova 2008 attempted to derive the magnitude of pre-historic earthquakes on southeastern Gomy Altai from the size of the largest landslides that triggered using an empirical correlation between the earthquake magnitude and the volume of associated landslides.
- Northridge, California Earthquake (17 January 1994, Mw-6.7) triggered thousands of landslides over a broad area. Landslides occurred primarily in young (Late Miocene through Pliocene) uncemented or weakly cemented sediments that has been repeatedly folded, faulted and uplifted in the past 1.5 million years. The most common types of landslides triggered by the earthquake were highly disrupted, shallow falls and slides of rock and debris. Far less numerous were deeper, more coherent slumps and block slides, primarily occurring in more cohesive and competent materials. To quantify and rank the relative susceptibility of each geologic unit to seismic landsliding, susceptibility index and frequency index have been used. Susceptibility Index is ratio (given as a percentage) of the area covered by landslide sources within a geologic unit to the total outcrop area of that unit and Frequency Index (given in landslides per square kilometer) is the total number of landslides within each geologic unit divided by the outcrop area of that unit. Susceptibility categories include very high (>2.5 % landslide area or >30 ls/km^2), high (1–2.5 % landslide area or 10–30 ls/km^2), moderate (0.5–1 % landslide area or 3–10 ls/km^2) and low (<0.5 % landslide area or <3 ls/km^2) as reported by Parise and Jibson (2000)
- A total of 4,134 landslides covering 19.7 km^2 that accounted for 6.4 % of the study area were reported from Anxian to Beichuan after the Wenchuan earthquake (12 May 2008, Ms-8.0). The number of landslides with areas less than 5,000 m^2 is upto 85.22 %. The smallest landslide is 6 sq.m and the largest is 1515,000 m^2. The number of landslides which have occurred is 1.6 times more prevalent in hanging walls as opposed to foot walls. Also the relationship between the number of landslides and distance to an earthquake rupture at a hanging wall is linear but exponential at a footwall. This indicates that landslide activity is more severe at hanging walls than at foot walls. (Yin et al. 2009)
- In the near field of causative faults, landslides tend to have the initial sliding direction similar to the movement of causative fault. It is indicated that landslide incidences vary in different slopes with different structure, and consequent slopes and obsequent slopes have a higher landslide incidences than the layered slopes (Qi et al. 2010)

- 2004 Mid Niigta prefecture earthquake (Mjma-6.8) triggered more than one thousand landslides in the Miocene to Quaternary sedimentary rocks in Japan. The most common landslides were shallow disrupted landslides on steep slopes. The earthquake triggered more than one hundred deep landslides. Reactivation of existing landslides and undercutting of slopes are the most important factors for deep landslides. In addition, planar sliding surfaces seem to be essential for the generation of catastrophic landslides. Planar bedding – parallel sliding surfaces were formed at the boundary between overlying permeable sandstone and underlying siltstone or along the bedding planes of alternating beds of sandstone and siltstone (Chigira and Yagi 2006).
- The Kashmir earthquake (8 October 2005, Mw-7.6) destabilized numerous slopes by creating a large number of tension cracks which may lead, together with the monsoonal climatic conditions, to increased landslide activity. The landslide inventory showed that 158 landslides were triggered along Balakot – Bagh fault. The most abundant type of active landslide was translational, which was mainly concentrated along the fault line in the Muzaffarabad Formation (Saba et al. 2010). Kamp et al. (2008) mapped 2,252 landslides after the Kashmir earthquake using satellite imagery. A multi-criterion evaluation was applied to determine the significance of event-controlling parameters in triggering landslides. The parameters included lithology, faults, slope gradient, aspect, elevation, landcover, rivers and roads. It indicated that lithology had the strongest influence on landsliding particularly when the rock is highly fractured. Moreover, the proximity of the landslides to faults, rivers and roads was also an important factor to initiate failure. Owen et al. (2008) reported that most of these landslides were mainly rock-falls and debris-falls, although translational rock and debris slides also occurred. In addition, a sturzstrom (debris avalanche) comprising ~80 million m^3 buried four villages and blocked streams to create 2 lakes. Although landslides occurred throughout the region, covering an area of >7,500 km^2, the failures were highly concentrated, associated with six geomorphic-geologic-anthropogic settings, including natural failures in (1) highly fractured carbonate rocks comprising the lowest beds in the hanging wall of the likely earthquake fault; (2) Tertiary siliciclastic rocks along antecedent drainages that traverse Hazara – Kashmir syntaxis; (3) Steep slopes (>50°) comprising Precambrian and Lower Paleozoic rocks; (4) very steep (>>50°) lower slopes of fluvially undercut Quaternary valley fills; (5) Ridges and spur crests and (6) Roads.
- The Avaj, Iran earthquake (22 June 2002, Mw-6.5) triggered landslides that include 47 falls and topple zones, 9 slides and 3 lateral spreads. The density of landslides decreases away from the fault zone in a manner that is asymmetric with respect to direction. Although several slides and lateral spreads were seen, the most common types of triggered landslides are falls and topples (Mahadavifar et al. 2006)
- Over 56,000 landslides were triggered by Wenchuan earthquake (12 May 2008, Ms-8), with a total area of 811 km^2. The spatial distribution of these landslides was analysed using Landslide Point Density (defined as the number of landslides per sq km) and the Landslides Area Density (the percentage of area affected by landslides) by Dai et al. (2011).

Impacts of Landslides

Primary impacts of earthquake landslides include

- Loss of human lives and livestock due to burial; Injuries to people being hit by landslides
- Loss of land, its productivity (in case of agricultural or farm lands) and revenue
- Loss of livelihood, living places, belongings, business, commercial and social activities
- Damage to building, structures, infra-structure and utilities located on failed slope
- Loss of trees in forest lands and damage to natural environment
- Clogging of damming of river channels (by debris, boulders and uprooted trees) forming landslide dammed lakes which burst and bring flash-floods on downstream side
- Sedimentation and inundation of reservoirs

Secondary impacts of the landslips are

- Modification in the forms of water courses. The dislodgement of large bodies of weathered rocks, and to no less an extent the consequent exposure of hill sides previously protected by forest, caused enormous volumes of sand to be cast into the streams. Thus, landslides not only change the morphology of the terrain but also an effective factor in sediment production. There still large quantities of sand not yet removed from the landslips and the bare faces of the hills will be the source of fresh supplies of sand as they are scoured by the rain, until such time as vegetation once more resumes its away. Often the channels are encumbered by innumerable landslips, forming a mass of boulders, gravels, sand and trunks of trees, carried down stream sometimes within and beyond the limits of hills.
- The burden of sand cast on to the streams was far greater than they could carry along their old gradients, and everywhere the beds have been raised, changing the whole character of the river channel in the process. Ordinarily, the beds of these rivers, which are raging torrents when in

floods, consist of succession of deep pools separated by rocky rapids. It was found that the pools had been filled up, and the rapids obliterated by a great deposit of sand, over which the rivers flowed in a broad and shallow stream. The remaining level of the river beds are raised due to debris brought down by the rain water. A remarkable instance was that of landslips near Sinya (1897 earthquake), to the east of Rambrai, which dammed up the drainage of a large area for nearly 3 months and gave the destructive flood.

Implications in Future Strategies and Programmes

The results of the above study can be applied in future strategies and programmes for development and disaster risk reduction in the following ways:

- Compile Inventory/Database of Earthquake Induced Landslides from the historical records of past earthquakes. This inventory will be used to improve the understanding of earthquake induced landslides and the casual relation between landslides and geo-environmental and triggering factors. The inventory should also include cascading hazards like landslide dams and flash-floods due to breaching of dams by landsliding. Identify the most common of types of slopes failures due to earthquakes.
- Assessment of the relationship between earthquakes and landslide characteristics, volume, velocity, frequency and spatial distribution. Establish relationship between number, type and size of landslide to the seismic parameters (earthquake magnitude, depth, distance from epicenter etc.)
- Landslide characteristics and their relationship between predetermined and predisposing factors should be evaluated.
- Landslides Relations with distance from focus/epicentre of earthquake, location on the fault plane (foot-wall and hanging wall), tectonic plane, slope aspect and form (concave and convex), location on slope (ridge or toe), degree of consolidation, extent of weathering, drainage, thickness of over-burden etc. to understand the seismic landslide susceptibility. The relationship of the interface between the overburden and bedrock (as well as different rock types) and depth of sliding is also important.
- Siting Guidelines for buildings, structures, Infra-structure and Utilities in Earthquake Prone Areas Susceptible to Landsliding (with main concern on landslides and slope stability under seismic action)
- Monitoring and assessment of landslide hazards in earthquake prone areas is an important task for decision making and policy planning in landslide prone areas.
- Disaster Management and Development programmes to include concerns for earthquake induced landslides in hilly terrains.
- Landslide micro-zonation studies to consider the impacts of earthquake and seismic micro-zonation studies to include the impacts of landslides. Identify the possible types of landslides, their characteristics and consequences.
- The influence of the precedent climatic conditions and effects of climate changes on landslide risks in earthquake prone areas should also be considered.
- Any new construction or rehabilitation or resettlement should consider slope stability and susceptibility to landslides in seismic hazard zones.
- Infrastructure development practice in the mountainous terrains prone to earthquakes, need extensive care on slopemass, morphology and aspects to reduce landslide risks.
- Existing zonation methods of earthquake induced landslides must be reviewed and compared with historical data information in order to define the most important triggering and susceptibility factors and to establish a method to assess them to be applied in an improved zonation methodology. At present, no such standard or code of practice exists in India.
- Establish relationship between seismic parameters and number of landslides, area affected by landslides and landslide characteristics including seismic shaking thresholds for triggering landslides

Conclusion

It may be concluded from the present study that there is an urgent need to systematically compile the database of earthquake induced landslides from the past earthquake and assess the relationships between earthquakes and landslides characteristics, volume, velocity, frequency and spatial distribution. There is a need to study the relation between magnitude of earthquakes and terrain characteristics like topography, geology, morphology, landuse and landcover conditions etc.

Scientific studies involving mapping of co-seismic and post-seismic landslides along with factors affecting their occurrence in terms of magnitude and impacts are very important to develop an appropriate understanding as well as strategy for earthquake risk mitigation and preparedness. The neglect of this field in the earthquake risk management of hilly terrains has proved quite costly in terms of lives lost and damages to the structures, infrastructure and services.

The lessons learnt from the past earthquake related landslide events clearly indicate that a pro-active mitigation and response strategy is needed to manage the consequences of any major earthquake in the hilly terrains of north east India. A proper documentation of the historical database of earthquake induced landslides would help in delineating the probable susceptible zones that may fail in future earthquakes. Most sensitive or susceptible conditions for earthquake related landslides have been found to be among the younger, unconsolidated or less consolidated fragile/fractured/laminated materials located in a high topography towards the ridges with steeper convex slopes and unfavorable orientations.

Based on these studies, the disaster management authorities and all other concerned department/ organizations can plan the developmental activities and prepare strategies to reduce the impending risks.

In general, topographical, geological, tectonic, seismic and climatic conditions, besides the uncontrolled anthropogenic interventions, are the common causes of earthquake related landslides that have large socio-economic and environmental impacts. The emerging issues related to climate change induced precipitation changes should also be considering in simulating scenarios for earthquake related landslides for future risk mitigation strategies and programmes. Development of siting guidelines for earthquake prone areas in hilly terrains which are susceptible to landslides, is essential for effectively reducing the envisaged risks.

References

Bhandari RK (2006) “Importance of earthquake induced landslides in landslide hazard mapping” keynote address at first India disaster management congress, New Delhi, 29–30 Nov 2006

Bommer Julian J, Rodriguez Carlos E (2002) Earthquake induced landslides in Central America. Eng Geol 63(3–4):189–220

Chang K-T, Chiang S-H, Hsu M-L (2007) Modeling typhoon and earthquake induced landslides in a mountainous watershed using logistic regression. Geomorphology 89:335–347

Chigira M, Yagi H (2006) Geological and geomorphological characteristics of landslides triggered by the 2004 Mid Niigta prefecture earthquake in Japan. Eng Geol 82(4):202–221

Chigira M, Wu X, Inokuchi T, Wang G (2010) Landslides induced by the 2008 Wenchuan earthquake, Sichuan, China. Geomorphology 118(3–4):225–238

Dai FC, Xu C, Yao X, Xu L, Tu XB, Gong QM (2011) Spatial distribution of landslides triggered by the 2008 Ms.8.0 Wenchuan earthquake, China. J Asian Earth Sci 40(4):883–895

Kamp U, Growley BJ, Khattak GA, Owen A (2008) GIS-based landslide susceptibility mapping for the 2005 Kashmir earthquake region. Geomorphology 101(4):631–642

Keefer DK (1984) Landslides caused by earthquakes. Bull Geol Soc Am 95:406–421

Keefer DK (2000) Statistical analysis of an earthquake-induced landslide distribution – the 1989 Loma Prieta, California event. Eng Geol 58(3–4):231–249

Khazai B, Sitar N (2004) Evaluation of factors controlling earthquake-induced landslides caused by Chi-Chi earthquake and comparison with the Northridge and Loma Prieta events. Eng Geol 71:79–95

Mahadavifar MR, Solyamani S, Jafari MK (2006) Landslides triggered by the Avaj, Iran earthquake of June 22, 2002. Eng Geol 86 (2–3):166–182

Meunier P, Hovius N, Haines JA (2008) Topographic site effects and the location of earthquake induced landslides. Earth Planetary Sci Lett 275(3–4):221–232

Nepop RK, Agatova AR (2008) Estimating magnitudes of prehistoric earthquakes from landslide data: first experience in southeastern Altai. Russ Geol Geophys 49(2):144–151

Oldham RD (1899) Report on the great earthquake of 12th June 1897, vol 29, Memoirs of the geological survey of India. Office of the Geological Survey, Calcutta, p 379

Owen LA, Kamp U, Khattak GA, Harp EL, Keefer DA, Bauer MA (2008) Landslides triggered by the 8 October 2005 Kashmir earthquake. Geomorphology 94(1–2):1–9

Parise M, Jibson RW (2000) A seismic landslide susceptibility rating of geologic units based on analysis of characteristics of landslides triggered by the 17 January, 1994 Northridge, California earthquake. Eng Geol 58:251–270

Qi S, Xu Q, Lan H, Zhang B, Liu J (2010) Spatial distribution analysis of landslides triggered by 2008.5.12 Wenchuan Earthquake, China. Eng Geol 116(1–2):95–108

Rodriguez CE (2006) Earthquake induced landslides in Colombia. ECI conference on Geohazards, Norway

Saba SB, Meijde M, Werff H (2010) Spatio-temporal landslide detection for the 2005 Kashmir earthquake region. Geomorphology 124 (1–2):17–25

Yin YP, Wang FW, Sun P (2009) Landslide hazards triggered by the 2008 Wenchuan earthquake, Sichuan, China. Landslides 6:139–152

Zhang D, Wang G (2007) Study of the 1920 Haiyuan earthquake induced landslides in loess (China), Enginerring Geology, 94(1–2):76–88