Hazard Specific Risk Assessment: Hydrological

2 - Landslide Hazard and Risk Assessment

Key words: landslide, landslide hazard, landslide vulnerability, landslide hazard map, risk management

The term 'landslide' refers to a variety of processes that result in the downward and outward movement of slope-forming materials, including rock, soil, artificial fill, or a combination of these. The materials may move by falling, toppling, sliding, spreading, or flowing. The schematics in Figure 1 illustrate the major types of landslide movement.

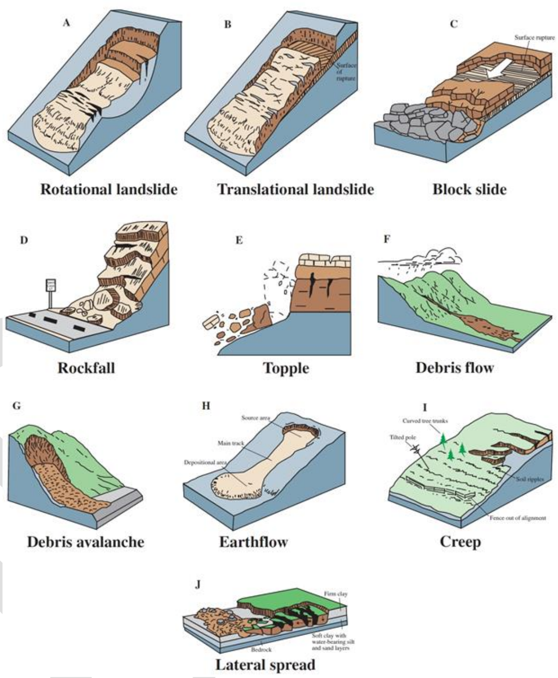

FIGURE 1 – Schematics illustrating the major types of landslide movement[1]

Landslides are a frequent natural hazard and a major threat to humans and the environment in many parts of the world. According to the International Disaster Database of CRED(EM-DAT)[2], since 1900 about 130,000 persons have lost their lives because of landslides and flash floods and the economic losses amounted to over US$50 billion. In the period 2000-2014, corresponding figures are about 26,000 deaths and US$40 billion. The actual figures are, however, much higher. In the CRED-EM database in fact, the losses due to earthquake-triggered landslides are attributed to earthquakes, and many landslide events with no casualties, but significant material losses are not reported. For example, 20 to 25% of the 87,000 casualties (69,000 confirmed killed and 18,000 missing) caused by Sichuan Earthquake of 12th May 2008 were due to the landslides triggered by that event[3]. Recent catastrophic

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landslides in Afghanistan, United States, the Philippines and India illustrate that landslides are still a major threat in developed as well as developing countries.

The volume of soil and rock mobilised in a landslide can vary from a small individual boulder to millions, and in rare cases billions, of cubic metres. Generally, the potential destructiveness of a landslide is a function of the volume of the masses that are mobilised, and their velocity, but even a single boulder can cause several fatalities.

Sources and setting

The primary driving factor of landslides is gravity acting on a portion of a slope that is out of equilibrium. The major landslide triggering mechanisms include: i) river erosions, glaciers, or ocean waves; ii) weakening of rock and soil slope proprieties through water saturation by snowmelt or heavy rains; iii) stresses, strains and excess of pore pressures induced by the inertial forces during an earthquake (is known that earthquakes of magnitude greater/equal 4.0 can trigger landslides); iv) volcanic eruptions with the production of loose ash deposits that may become debris flows (known as lahars) during heaving rains; v) stockpiling of rock or ore, from waste piles, or from man-made structures; and vi) changes of the natural topography caused by human activity.

Landslides are strongly associated with, and often triggered by, other types of natural hazards such as extreme precipitation during storms; earthquakes; volcanic eruptions; floods; and to some degree droughts and wildfires. Furthermore, a large submarine landslide can trigger a tsunami. Because of their strong correlation with other hazards, landslides are often involved in cascading events (domino effects) of multi-hazard disasters.

Landslide hazard assessment

Landslide hazard is a function of susceptibility (spatial propensity to landslide activity) and temporal frequency of landslide triggers, and its assessment may be done at local (individual slope), regional, national, continental, or even global scales. The most appropriate method in each scale depends on the extent of the study area and on the available data. Examples of various methodologies for landslide hazard assessment at different scales can be found in the literature[4,5,6,7].

In any type of landslide hazard assessment, there is a need to consider topography and other factors that influence the propensity to landslide activity (susceptibility factors) as well as landslide triggering factors (precipitation, earthquakes, human activity). Table 1 lists the input data typically required for landslide hazard assessment at regional to national scales.

TABLE 1 - Sources of data for landslide risk assessments at regional and national scale

Description of Input Data	The national entities that most commonly have this data	Examples of Existing open databases available from international sources
Digital elevation model (DEM)	National mapping and cartography authority	SRTM30 (NASA)[8]
Lithology	National geological survey	UNESCO (CGMW, 2000), One Geology initiative[9]
Vegetation cover	National agriculture/environment and/or national forest agency	GLC2000 database[10]
Soil moisture factor	National agriculture/environment and/or national meteorological agency	Climate Prediction Center (CPC)[11]
Hourly, daily, and monthly precipitation	National meteorological agency	Global Precipitation Climatology Centre (GPCC) run by Germany's National Meteorological Service, DWD[12]
Seismicity	National building code(s)	Global Seismic Hazard Program (GSHAP)[13], Global Earthquake Model (GEM)[14]
Infrastructure and road/railway network in mountainous regions	National road and/or railway authority	Google maps

There are many sources and types of uncertainty in landslide hazard assessment. By far, the main source of uncertainty is the epistemic uncertainty related to our limited knowledge about the materials that make up the slope(s), their response under various external perturbations, and the characteristics of the triggering factors. Furthermore, soils, rocks and other geomaterials exhibit significant spatial variability (aleatory uncertainty) and their properties often change markedly over small distances. Many non-local scale landslide hazard assessment models are empirical and should be calibrated/validated with regional and/or national database(s) of previous landslide events. Landslide inventory maps are often an important input for the landslide susceptibility/hazard assessment and/or validation. However, one must keep in mind that even in developed countries, the databases of landslide events are usually far from complete. Often they only cover the events from the recent past, and/or have an over-representation of landslides triggered by a single extreme event, and/or are heavily biased towards the events reported by a single source, like the national road or the rail authority.

Climate change increases susceptibility of surface soil to instability because of abandoned agricultural areas, deforestation and other land cover modifications, anthropogenic activities and uncontrolled land-use are other important factors that amplify the uncertainty in landslide hazard assessment.

Exposure and vulnerability assessment

Exposure of population and/or built-up environment to landslide risk can be assessed by superimposing landslide hazard map(s) with maps of population density, the built environment and infrastructure. However, this type of assessment provides only a qualitative picture of the exposure to landslides. Landslides vulnerability assessment is a complex process that should consider multiple dimensions and aspects, including both physical and socio-economic factors. Physical vulnerability of buildings and infrastructure[15,16,17,18,19,20] is a function of the intensity of the landslide event and the resistance levels of the exposed elements.

Societal vulnerability and resilience of a community, on the other hand, are related to factors such as demographics, preparedness levels, memory of past events, and institutional and non-institutional capacity for handling natural hazards. Although there is significant literature[21] of assessment of societal vulnerability to natural hazards very few studies address specifically the social and economic vulnerability to landslides are available. In the SafeLand project, an indicator-based methodology was developed to assess the (relative) societal vulnerability levels. The indicators represent the underlying factors that influence a community's ability to deal with, and recover from the damage associated with landslides[22, 23]. The proposed methodology includes indicators that represent demographic, economic and social characteristics like human development index (HDI) and GDP, as well as indicators representing the degree of preparedness and recovery capacity. The purpose of the societal vulnerability assessment is to set priorities, serve as background for action, raise awareness, analyse trends and empower risk management.

Risk assessment use in national DRR measures

Studies on global distribution of landslide hazard[24] as well as detailed assessment of the reported occurrence of landslide disasters in the CRED-EM database suggest that the most exposed countries to landslide risk are located in south Asia, along the Himalayan belt, in east Asia, southeast Asia, and in Central and South America.

In most developed countries with high landslide hazard, landslide events rarely end up as disasters. This is mainly due to the low exposure in the most landslide-prone areas, as well as the increasing ability to identify the landslide-prone areas and to implement appropriate landslide risk management actions.

Many countries that have areas with high landslide hazard lack the necessary legislation and regulations to prioritize and implement landslide risk mitigation plan. Often it is asserted that it "takes a disaster to get a policy response", and case studies of landslide risk management in different countries show a relationship between the incidence of disasters, and progress and shifts in landslide risk management[25]. Disasters can catalyse moments of change in risk management aims, policy and practice. Increasingly, the decision-making processes of the authorities in charge of reducing the risk of landslides and other hazards are moving from "expert" decisions to include the public and other stakeholders in the decision process[26].

In practice, effective landslide risk mitigation should be implemented at local (individual slope) or regional level. At local scale, the design of a risk mitigation measure, for example an Early Warning System, can be based on a number of reasonable scenarios and may involve the following steps: (1) define scenarios for triggering the landslide(s) and evaluate their probability of occurrence; (2) estimate the volume and extent of the landslide and compute the run-out distance for each scenario; (3) estimate the losses for all elements at risk for each scenario; (4) compare the estimated risk with risk acceptance/risk tolerance criteria; and (5) implement appropriate risk mitigation measures if required. It is not clear that this level of rigour is always practiced in landslide risk management, especially in poor countries where resources are limited.

Good practice of landslide risk management

One of the best example of good landslide risk management practice is found in Hong Kong. Hong Kong is situated on the south-eastern coast of China, has a sub-tropical climate with annual average rainfall of 2300 mm, peaking in the summer, with regular rainfall events with intensities exceeding 100 mm/hour. Hong Kong has a small land area of about 1100 km^2, over 60% of which is located on hilly terrain, and its population has increased steadily from 2 million in 1950 to over 7 million today. This has led to a huge demand for land for residential use and infrastructures, and resulted in a substantial portion of urban development located on or close to man-made slopes and natural hillsides. Man-made slopes that are not properly designed and steep hillsides are susceptible to landslides during heavy rainfall, and debris flows are common in natural terrain. As a result, landslides are a key natural hazard in Hong Kong where can cause significant casualties and social-economic impacts.

On 18th June 1972, after days of heavy rainfall, two destructive landslides in Sau Mau Ping and at Po Shan Road in Hong Kong killed one hundred thirty-eight people, covered a resettlement area with landslide debris and caused a high-rise building to collapse completely. In 1977, in the aftermath of these and other fatal landslide disasters, the Geotechnical Control Office (GCO) (now the Geotechnical Engineering Office, GEO), was set up to strategically implement a comprehensive system to maintain slope safety. The Slope Safety System developed by GEO comprises several initiatives to reduce landslide risk in a holistic manner. The key components of the system are comprehensive enforcement of geotechnical standards, community participation for slope safety, systems for early warning and emergency response, and maintaining comprehensive databases of landslide events and implemented risk mitigation measures. Several studies show that the implementation of the Slope Safety System has reduced the annual fatalities due to landslides by over 50% since the late 1970's[27]. There have been no fatalities due to landslides in almost a decade.

Programmes that have achieved this level of success are rare and are obtained at considerable cost. In developing countries, there are few, if any, examples of successful nationwide reduction in landslide losses as a result of such initiatives. Landslides are amongst the most potentially manageable of all natural hazards, given the range of approaches and techniques that are available to reduce the level of hazard. There is real scope to reduce their impacts.

Resources for further information

The following sources provide useful information and tools for landslide hazard and risk assessment, and landslide risk management:

- European Commission's FP7 Project SafeLand[28]
- Landslide Guidelines of Geological Survey of Canada[29]
- International Consortium on Landslides[30]
- USGS landslide hazards program[31]
- Hong Kong slope safety – Geotechnical Engineering Office[32]
- UNISDR's Global assessment reports on disaster risk reduction[33]
- MoSSaiC: Management of Slope Stability in Communities[34]

Authors: Farrokh Nadim (Norwegian Geotechnical Institute)

Contributors and Peer Reviewers: Bjørn Kalsnes (NGI), Dave Petley (Sheffield University), Michel Jaboyedoff (University of Lausanne), Nicola Casagli (University of Florence), Paola Reichenbach, Fausto Guzzetti (Italian National Research Council)

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