GIS Application in Landslide Hazard Analysis

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Abstract

Landslide is one of unpreventable phenomenal disaster such as earth quick and volcanoes. All of geological risks, landslides are among those cause most damage thousands of deaths every year and material losses of billions of dollar. Landslide characterization is fundamental step leads to landslide risk assessment. From literature review the landslide risk assessment went through developments which occurred in last decade. Technologies such as Geographical Information Systems (GIS) have great role in quantification and predicting the risk of landslide which consequently assist the urban planners and officials to take the best scenarios of their decisions. There is an unfortunate general tendency to search for data which can be collected at low cost rather than attempting to capture the information which most readily explains the causes of a disaster.

This paper provide the workflow and methodology to quantify landslide risk over larger areas, the generation of landslide inventory maps including information on date, type and volume of the landslide, the determination of its spatial and temporal probability, the modeling of rainout and the assessment of landslide vulnerability. Hong kong landslide case study provided as example of different approaches to landslide hazard and risk zonation at medium scales area. This paper concludes with a number of new advances and challenges for the future, such as the use of very detailed topographic data, the generation of event-based landslide inventory maps, the use of these maps in spatial-temporal probabilistic modeling and the use of land use and climatic change scenarios in deterministic modeling.

Introduction

Landslides can be noticed in many different forms, including rock falls, rockslides, debris flows, soil slips, rock avalanches, and mud-flows. The scale of landslide hazard can be expressed in either regional basis, community basis or a site basis. When landslide hazard is estimated, we have to consider the historical records, the local geology (e.g. shallow or deep-seated landslides),lithology (e.g.physical and chemical behaviors of rocks and soils), structure (e.g. stratigraphic sequences, joint sets etc), geomorphology (e.g. steepness of slopes), hydrologic conditions (e.g. groundwater level), vegetation (e.g. form and type of vegetative cover), and climate (e.g. precipitation and temperature). The local stress condition is also an important factor that may relate to uplift, erosion, deposition, and groundwater fluctuation. Many of these parameters and conditions actually change with time. The most reliable way to prevent landslide-induced casualties and economic losses is to avoid building towns or cities in the area of steep terrains. But, this is considered impracticable or impossible in many countries due to the rapid growth of human population or due to the expensive cost in relocating of ancient or historical cities. Thus, regional landslide hazard analysis and management is becoming an important task for city planners and officials.

Definition of landslide risk

The most useful dentition of landslide risk is presented by Varnes (1984) as ‘‘the expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular damaging phenomenon for a given area and reference period’’. Dealing with physical losses, specific risk is quantified as the product of vulnerability, cost or amount of the elements at risk and probability of occurrence of the event with a given magnitude or intensity. The total risk is the hazard which is multiplied with the expected losses for all different types of elements at risk (vulnerability · amount), and this is done for all landslide types. Schematically, this can be represented by the following formula, based on Varnes (1984), Fell (1994), Leroi (1996) and Lee and Jones (2004):

$$\text{Risk} = \sum \left(H \sum (VA) \right)$$

Where: **H**: Hazard expressed as probability of occurrence within a reference period (e.g., year, design period of a building). Hazard is a function of the spatial probability (related to static environmental factors such as slope, strength of materials, depth, etc.) and the temporal probability, related indirectly to some static environmental factors like slope and hydraulic conductivity and directly to dynamic factors like rain input and drainage

V: Physical vulnerability of a particular type of element at risk (from 0 to 1) for a specific type of hazard and for a specific element at risk

A: cost of the particular elements at risk (e.g., number of buildings, cost of buildings, number of people, etc.)

The calculation of the consequences (**VA**) has to be done for all elements at risk, and the results added for one particular landslide hazard (the probability for a specific combination of landslide type and magnitude). The specific risk would result in a single value of potential losses for a given probability. The formula would result in a so-called risk curve, containing the relation between all events with different probabilities, and the corresponding losses, which forms the basis for the phases of risk reduction, risk transfer and planning (Lee and Jones 2004).

The risk formula looks deceptively simple, but it is very difficult to locate exactly the element at risk versus the possible locations of the landslides. The use of the formula requires the analysis of the spatial and temporal probabilities that groups of elements at risk in the map are hit by mass movements of different particular magnitudes, which are then used to estimate the degree of loss.

Landslide causes and impacts

Landslides are classified according to their movement types and the nature of the displaced material, as well as information on their activity (state, distribution, style), ie. The rate of development over a period of time (Varnes, 1978; Dikau et al. 1996; Cruden and Varnes 1996). Five principal types of movements are distinguished according to the geomorphological classification proposed by Cruden and Varnes (1996) and Dikau et al. (1996).

- **Fall**

A mass of fragmented material travel through slope of movement includes free fall movement by leaps and bounds or rolling .This movement occurred when little or no shear displacement developed at the steep slope. (Fig 1)

Figure 1: Showing movement of fragmented rocks travel by rolling through slope movement when shear displacement developed at the base of steep slope (source USGS landslide types and processes)

➢ Topple

A slope movement that occurs due to forces that cause an over-turning moment about a turn point below the centre of gravity of the slope. A topple is very similar to a fall in many aspects, but do not involve a complete separation at the base of the failure (Fig 2)

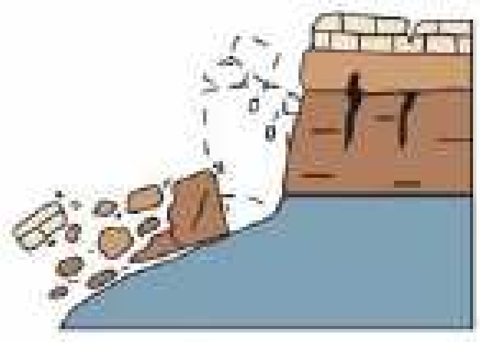

Figure 2: Showing movement of fragmented rocks travel by rolling due to weak point under the center gravity of the slope (source USGS landslide types and processes)

➢ Lateral Spreading

Lateral extension movement of major rigid mass over deforming softer one which controlling the basal shear surface (Fig 3).

Figure 3: Showing movement of rigid rocks due to lateral extension which underling by softer material at the basal of shear surface (source USGS landslide types and processes)

Lateral Spreading

The material is displaced more or less coherently along a recognizable or less well-defined shear surface or band. Slide could be rotational (the sliding surface is curved) or translational (the sliding surface is more or less straight). In some cases a slide can change into a mudslide or slump-earth flow, especially on steep slopes, in highly structurally active clays or silty formations (Picarelli, 2001).

A: Rotational slide: more or less rotational movement, about an axis that is parallel to the slope contours, involving shear displacement (sliding) along a concavely upward-curving failure surface, which is visible or may reasonably be inferred' (Varnes, 1978).

B: Translational slide: The material displaces along a planar or undulating surface of rupture, sliding out over the original ground surface (Fig 4)

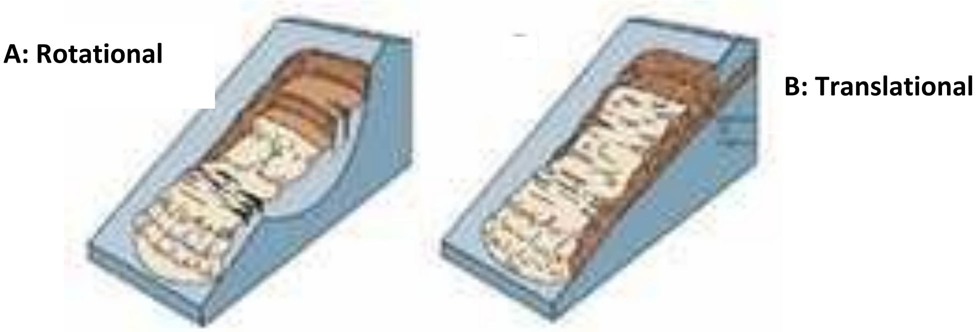

Fig 4: Showing two types of movement (A) rotational involve slope movement with upward curving failure (B) translational slide due to material displaced a long planar surface (source USGS landslide types and processes)

- **Flows**

The slope of movement is characterized by internal differential movements that are distributed throughout the mass and in which the individual particles travel separately within the mass (Fig 5) Debris flow is a very rapid to extremely rapid flow (> 1 m.s $^{-1}$) of saturated non-plastic debris in a steep channel. Characteristic of a debris flow of a debris flow is the presence of an established channel or regular confined path, unlike debris avalanches which are thin, partly or totally saturated and which occur on hill slopes (Hungr et al 2001).

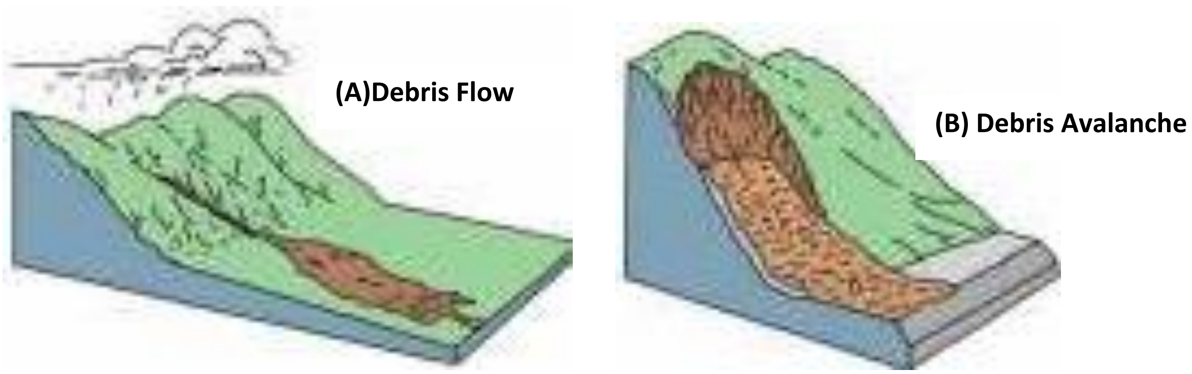

Fig 5: Showing two types of flow movement (A) Debris Flow Characteristic by very fast flow and established channel (B) Debris Avalanche characterized by water saturated and occurred on hill slopes (source USGS landslide types and processes)

Common triggering factors of slope movements

A failure occurs when the disturbing forces create movement exceed the resisting forces of the material. Triggering factors may either increase the shear stress; decrease the shearing resistance of the material or both. The shape and size of slope movements vary because of the combination of several preparatory and triggering factors (dissolution, deformation and rupture by a static or dynamic load). They may be controlled by the topography (inclination and shape of the slope), the lithology (physical and geomechanical characteristics), the geological structure (dip, fault, and discontinuity), the hills slope hydrology (pore pressures, water contents) or a combination of all these factors. The consequence for the slopes is a reduction in the inter-particle forces and the associated friction throughout the length of water acts as an agent in the transport of materials (Van Asch et al., 2007)

Increase in shear stress

- Erosion and excavation at the toe of the slope
- Subterranean erosion (piping)
- Surcharging and loading at the crest (by deposition or sedimentation
- Rapid drawdown (man-made reservoir, flood high tide, breaching of natural dams)
- Earthquake
- Volcanic eruption
- Modification of slope geometry
- Fall of material (rock and debris)

Decrease in shearing resistance

- Water infiltration (rainfall, snowmelt, irrigation, leakage of drainage systems)
- Weathering (freeze and thaw weathering, shrink and swell weathering soil)
- Physico-chemical changes
- Fatigue due to static/cyclic loading and creep
- Vegetation removal(by erosion, forest fire, drought or deforestation)
- Thawing of frozen soils

Possible increase in shear stress and decrease in shearing resistance

- Earthquake shaking
- Artificial vibration (including traffic, pile driving, heavy machinery)
- Mining and quarrying (open pits, underground galleries)
- Swinging of trees

Landslide Risk Assessment Methodology and work flow

The objective of landslide risk evaluation is to determine the expected degree of loss due to a landslide and number of live lost, people injured, damage to property and disruption of economic activity (Varnes et al., 1984). It started with the identification and the description of the threat, to succeed towards an evaluation of the claimed exposure and a characterization of the risk. The hazard analysis is based on four fundamental assumptions:

1. Landslides will always occur in the same geological, hydrological conditions as in the past.
2. Main condition caused landsliding are controlled by physical factors
3. Degree of hazard can be evaluated.
4. All types of slope failures can be identified and classified.

Generally, landslide risk assessments are carried out using the risk based framework described in Fig 6. The risk assessment initiated with analysis of hazard and consequences, then the process of establishing a measure of risk is referred to risk estimation. Risk assessment culminates by risk evaluation where levels of risk will determine prevention measures.

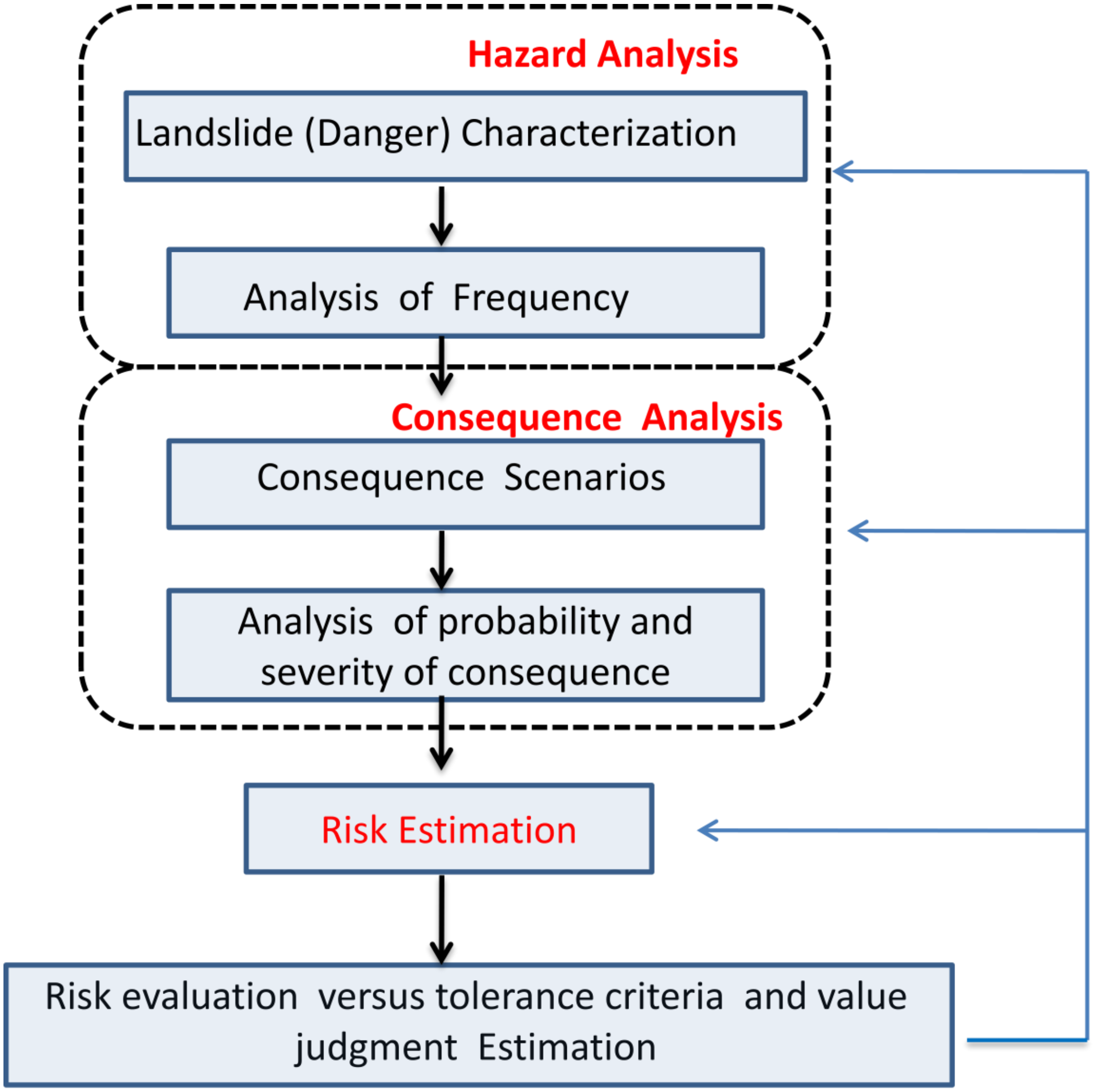

Fig 6. Workflow for landslide quantitative risk assessment (after Fell et al., 2005)

A schematic overview of the procedure for a GIS-based landslide risk assessment at a large or medium mapping scale (e.g., 1:10,000–50,000) is given in Fig.7. The top of the methodology displays the four basic types of input data required: environmental factors, triggering factors, historic landslide occurrences and elements at risk. The historic information on landslide occurrences is the most important, as it gives insight into the frequency of the phenomena, the types involved, the volumes and the damage that has been caused.

Landslide inventory maps, derived from historic archives, field data collection, interviews and image interpretation are essential but unfortunately lacking of the data create a challenge to identify the triggering factors consisted of earthquake and rainfall records, which have to be converted into magnitude–frequency relations of those aspects that actually trigger landslides, e.g., earthquake acceleration or groundwater depth. These parameters are based on collected information from sites. It can only be modeled properly using deterministic (geotechnical or hydrological) models. It required considerable input on the geotechnical characterization of the terrain (soil depth, cohesion, friction angle, permeability).

Determining temporal probability is done either by correlating the data on landslide occurrences with those the triggering factors (provided that the historical records are sufficient for this) or through dynamic modeling (Van Beek 2002). The spatial probability can be obtained either through dynamic modeling or through analyzing the relation between the locations of past landslide events and a set of environmental factors, in order to predict areas of landslide initiation that have similar combinations of factors, using statistical methods.

The spatial information on landslide initiation locations is used in combination with the environmental factors.The Digital Elevation Model (DEM) is the most crucial one, in the modeling of the run out distance for landslides of a particular type and volume. The combination of landslide initiation zones, with temporal and spatial probability, and run out zones results in a landslide hazard map. However, most hazard maps are still of a qualitative nature and concentrate basically on determining the susceptibility. Determining temporal probability is often not possible; due to the absence of historical landslide records that effectively can be related with the historical records of the most important triggering events (rainfall and earthquakes), scarcity of input data, or the absence or insufficient length of historical records of the triggering events.

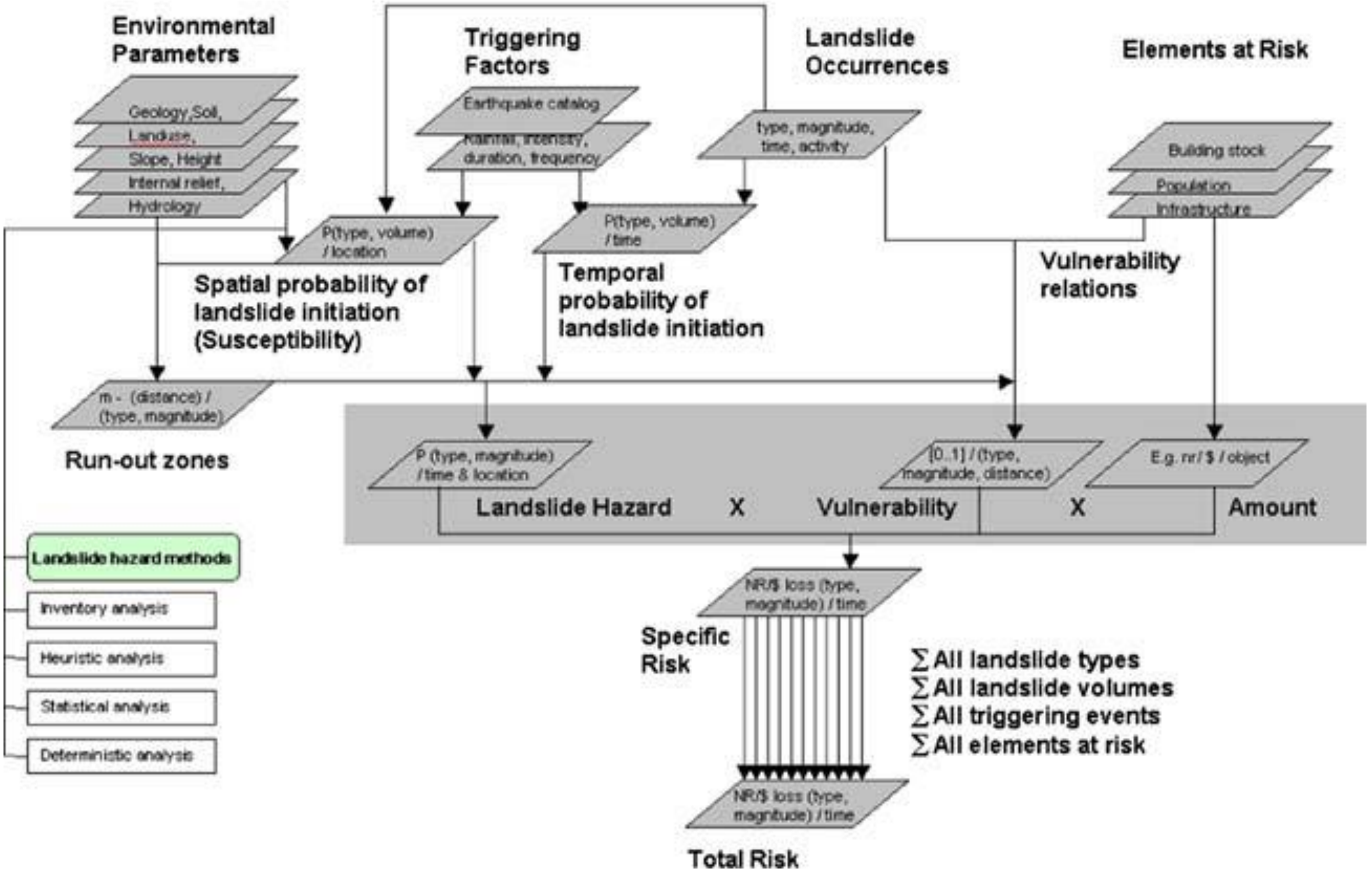

Fig.7. Schematic representation of spatial landslide risk assessment methodology (Van Westen.,2003)

Case Study of Hong Kong Landslide

Before starting the discussion of the land slide hazards of Hong Kong, it is preferable to have a brief introduction about geological and climatic conditions of Hong Kong Island.

Geological conditions of Hong Kong Island

Hong Kong can be divided into three distinct areas: Hong Kong Island, Kowloon and the New Territories. The area of Hong Kong Island is 77.5 km^2, or about 7% of the total area 1098 km^2 of Hong Kong. The terrain of Hong Kong Island consist hills and mountains with steep slopes exceeding 30 degree, covered by superficial deposits of Quaternary age. The highest point is the Victoria Peak at 554 m. Fig. 8 shows an aerial photograph of the hilly Hong Kong Island and Kowloon Peninsula

Fig 8. Aerial photograph of Hong Kong Island and Kowloon Peninsula (after Fyfe et al., 2000)

The location of the photograph in Hong Kong is shown in Fig.9. Hong Kong Island is underlain mainly by volcanic rock and intrusive granite. In general, the outcropping rocks of Hong Kong are highly weathered, and a mantle of debris flow deposits covers the north-facing slopes of Victoria Peak. The deposits come almost entirely from the volcanic rocks around the Peak. In most places the average thickness of the deposits is about 2 m, but in some places the deposits may be up to 30 m. In addition, talus deposits have also been delineated at three locations of the north-facing slopes of Victoria Peak (Fyfe et al., 2000).

Climatic conditions of Hong Kong

Hong Kong's climate is sub-tropical, with a winter temperature of 10 C to summer temperature of exceeding31C. Foggy weather is expected from March to May, while a hot and humid weather with occasional showers and thunderstorms, and frequent typhoon visits from May to September. When a typhoon comes close to Hong Kong, rain can become heavy and widespread and last for a few days. Subsequent landslides are commonly observed. The mean annual rainfall ranges from around 1300 mm along the coast to more than 3000 mm on mountains. About 80% of the rain falls between May and September; and the wettest month is August with an average monthly rainfall of about 400 mm.

Landslides hazard analysis based on landslide inventory. They are mainly extracted from the reports on ''Hong Kong rainfall and landslides'' which are published annually by the Geotechnical Engineering Office since 1984 and from a report compiling all landslide consequences since 1948 (GEO, 1996). Data before 1984 are incomplete since only landslides involving injuries and fatalities were included. The latest reports (1992– 1996) seem to be much more complete than those reports before 1992. Also, the volume of landslides is missing in reports before 1992 and exact occurrence time is missing in many earlier entries. Rock fall data has not been included in the present analysis since they have been analyzed by Chau et al. (1998, 2003). Another caution must be made is that most of the landslide records are for the failures of man-made slopes. For landslides on natural terrains, only those events leading to death, injury, or interruption of human activities have been included. For non-damaging natural terrain landslides, the locations of their occurrence must be close to human activities that caught the attention and caused concerns of the nearby residents, otherwise they will not be reported. Fig. 10 shows some landslide events in Hong Kong.

Fig. 10(a) shows the debris flows occurred on the natural terrain on Lantau Island in November 1996; Fig. 10(b) shows the Shun Wan Road landslide occurred on August 13, 1995, which involves a total of 26,000 m of sliding mass and leads to 2 death and 5 injured; Fig.10(c) shows the Po Shan Road landslide occurred on June18, 1972, which leads to 67 deaths and severe damages to a 12-storey building; and finally Fig. 10(d) shows the TsingShan debris flow occurred on April 14, 2000.Although it is very unlikely that the data compiled here are complete, this data set is considered reliable and should constitute a good basis for hazard analysis.

Diurnal and seasonal distributions for landslides in Hong Kong (1948–1996) Diurnal rock fall frequency was established by Chau et al. (1998) for Hong Kong by using129 data from 1949–1995. There is, however, no counterpart study for landslide data of Hong Kong. Therefore, plots the diurnal landslide distribution by compiling a total of 623 data from 1948 to 1996. It appears that landslides often occur during day time from 7 in the morning till 6 in the evening.

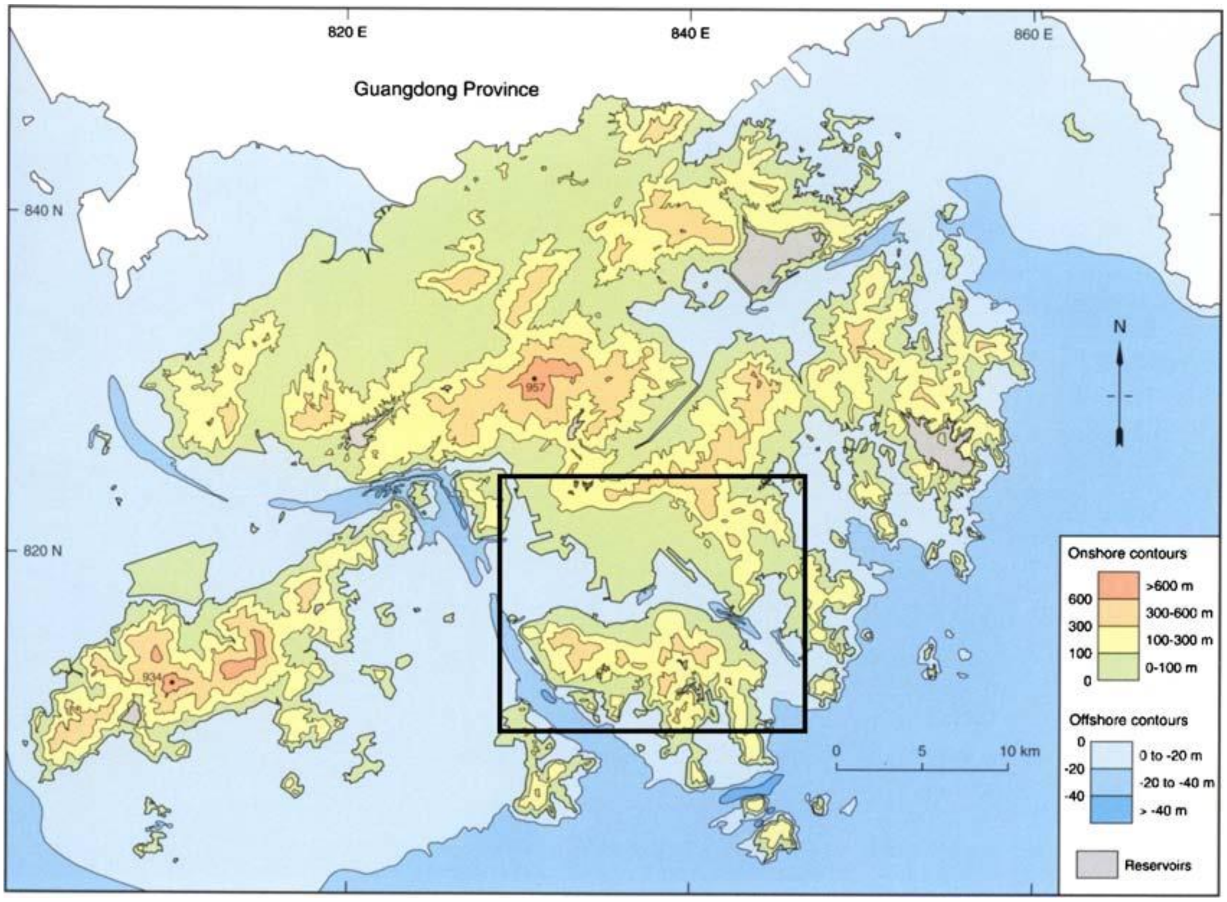

Fig .9. Contour map of Hong Kong with coverage of photograph shown in Fig. 4 highlighted by a rectangle. (Chau et al.,1998)

Fig.10. Some landslides in Hong Kong: (a) debris flows on natural terrain of Lantau Island in November 1996; (b) ShunWan Road landslide on August 13, 1995 with a total of 26,000 m3 of sliding soil and leading to 2 dead and 5 injured; (c)Po Shan Road landslide on June 18, 1972 leadingto 67 death and severe damages to a 12-storey building; and (d) Tsing Shan debris flow on April 14, 2000. (Chau et al.,1998)

The peak hour of landslide occurrence is at noontime. However, we should bear in mind that during the daytime human activities are more active, thus the chance of triggering a landslide occurrence is higher than that during the nighttime. This conclusion is similar to that for the diurnal distribution for rock fall occurrence reported by Chau et al. (1998).

Plots the seasonal distribution for landslides occurred in Hong Kong Island together with the average daily rainfall and temperature. A total of 1448 data from 1984 to 1996 were plotted. Except for the month of May, the average monthly rainfall correlates very well with landslide occurrence may have an abnormal high .Fig 11

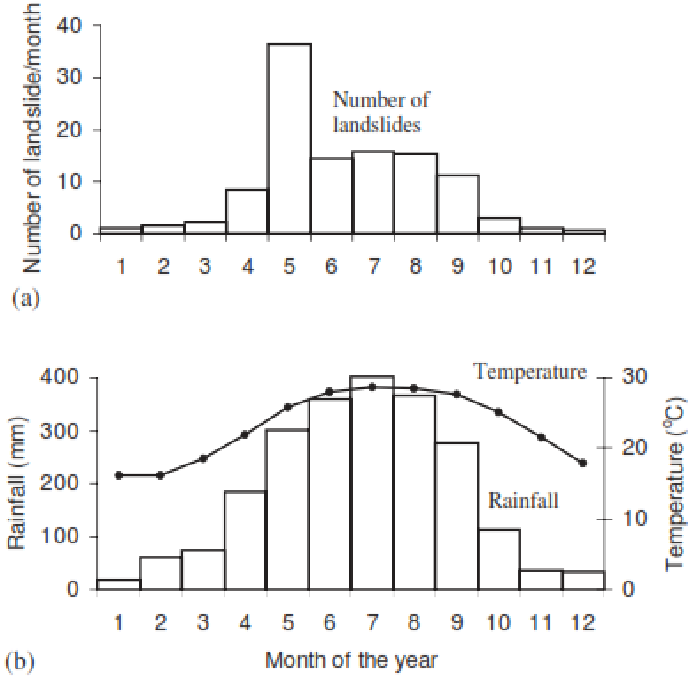

Fig. 11. (a) Seasonal variations of average landslide frequency in Hong Kong (1984–1996); and (b) seasonal distributions of rain fall (columns) and temperature (solid line with dots). Total number of landslide data used in the analysis is 1448. (Chau et al.,1998)

It is of interest to know, at least statistically, where in Hong Kong or what kind of facilities is at a higher risk. Fig. 12 plots the cumulative number of events having influences on squatter (damage or evacuation), road (blockage or damage), footpath (blockage or damage), building (damage or evacuation), and open space (no direct influence) from 1984 to 1996. Note that some of these landslide events may affect more than one type of facilities; therefore, double count of influences is allowed in our analysis.

As shown in Fig.13, squatter areas in Hong Kong are at the highest risk, following by roads, pedestrian pavements or footpaths, and buildings. In recent years, landslide hazard on squatter is dropping while that for road and footpath is increasing. This is due to the rapid expansion of the highway system in Hong Kong in recent years and the gradual decrease of squatter areas because of public housing policy.

Fig. 8 shows that 28% of landslides land on squatter areas, 22% on road, 18% on footpath, 10% on open space, 10% on buildings, 5% on public facilities, 3% on retaining walls and drains, 3% on car-parks and the remaining1% on vehicles. The very low rate of direct hit on car suggests that the landslip warning system adopted by the Hong Kong Government during heavy rainfall has been effective in reducing fatality or injury on roads and highways.

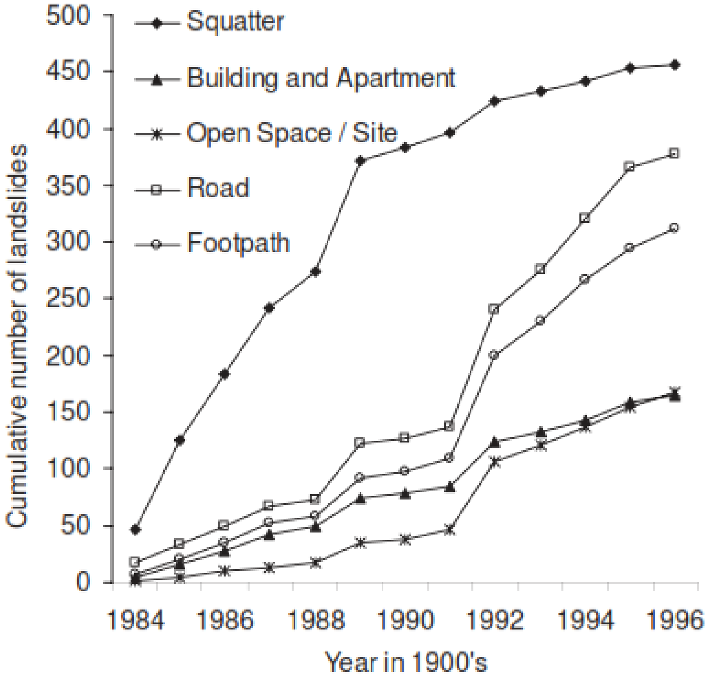

Fig.12. Cumulative number of landslides affecting various facilities and utilities from 1984 to 1996, including squatter, road, footpath, open space site, and building, apartment.(Chau et al.,1998)

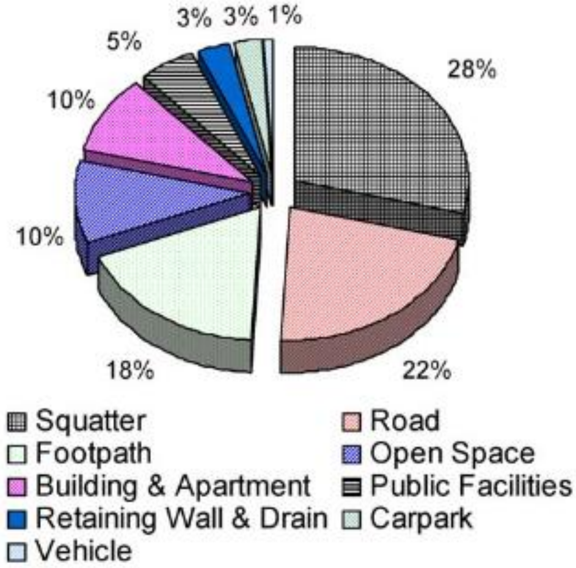

Fig. 13. Percentage distribution of landslides landing on squatter, road, footpath, open space, buildings, public facilities, retaining wall and drain, car park and vehicle.(Chau et al.,1998)

To eliminate subjective bias in estimating the potential runout of landslides, numerical model based on debris flow dynamics should be used to simulate the hazardous zone. Such analysis is, however, out of the scope of the present study. Regarding the rainfall layer, it is debatable on how to incorporate rainfall into the hazard analysis. In this study, the monthly rainfall map with the maximum value within the 11 year period from 1990 to 2000 are extracted and averaged using raster calculation to yield of rainfall hazard raster map. The hazard maps for these seven layers of parameters are shown in Fig.9.

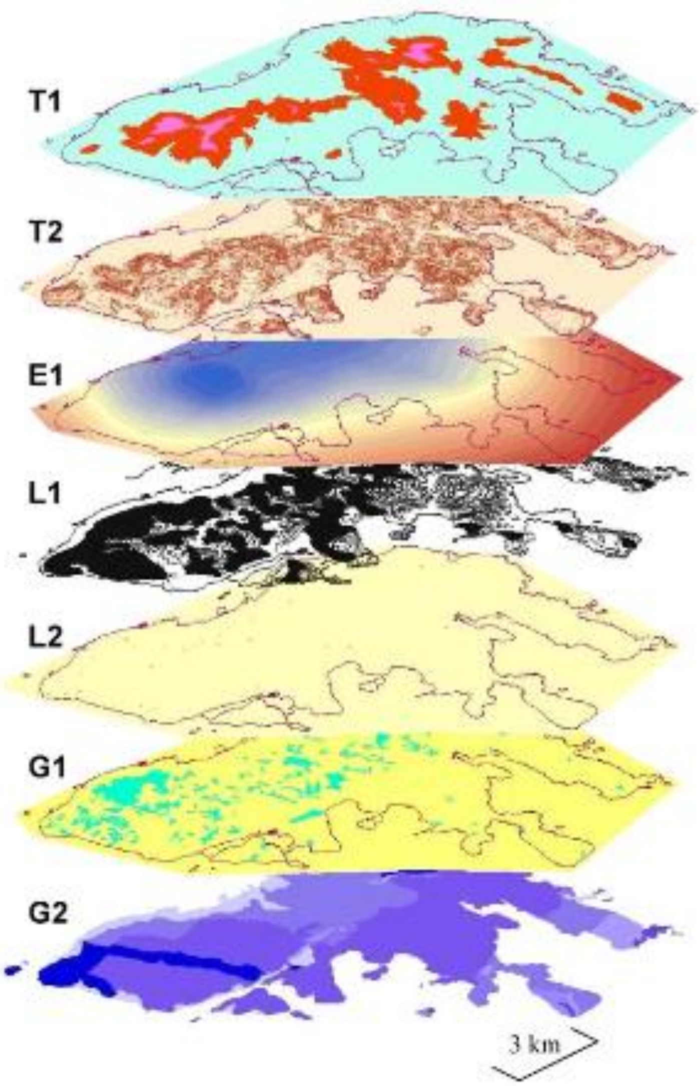

Fig. 9. Seven layers of GIS maps used in generating landslide hazard map for Hong Kong Island (from top to bottom):T1=elevation; T2=slope; E1=rainfall; L1=potential runout of landslides; L2=landslide inventory; G1=soil deposition; G2=geology (Chau et al.,1998)

In general, the vulnerability of other exposures to landslides hazard, such as transportation system, buildings and public facilities. Again, the risk map shown in Fig. 10 is given for illustrative purposes where it shows the concentration of rainfall and high slope. These two parameters are crucial to be predicted accurately in order to study potential risk of landslide and provide and warnings to people who lived in area expected to be affected by landslide.

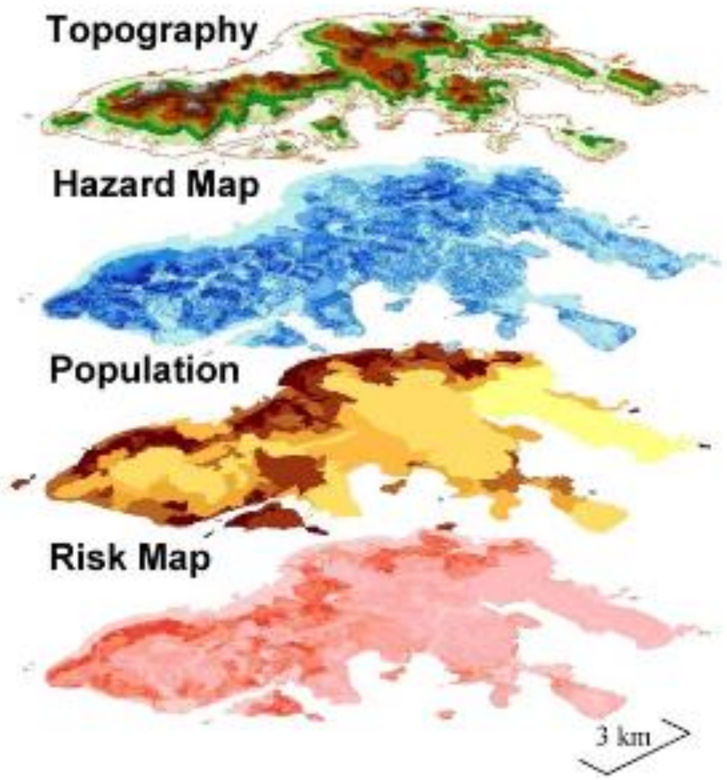

Fig. 10. Hazard map generated by layers of information from Fig. 8 together with risk map. Risk map is product of hazard map and scaled population map; and topography layer is given for reference (Chau et al.,1998)

Based on 1448 landslide data from 1984 to 1998, diurnal and seasonal distributions of landslides have been established. The cumulative fatalities and injuries caused by landslides are plotted against cumulative rainfall in Hong Kong. Total number of fatalities and injuries are 556 and 570, respectively, from 1948 to 1996. A total of 258 landslide events led to either death or injury, 117 of them killed 556 people. The average number of fatality and injury per year is 11.35 and 11.63, respectively. The integration of landslide risk assessment with city planning will provide a tremendous help to officials to take their decision when a disaster occurred

Conclusion

landslide risk is presented by Varnes (1984) as ‘‘the expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular damaging phenomenon for a given area and reference period’’. Landslide inventory maps, derived from historic archives, field data collection, interviews and image interpretation are essential but unfortunately lacking of the data create a challenge to identify the triggering factors. Most hazard maps are still of a qualitative nature and concentrate basically on determining the susceptibility. The temporal probability is done either by correlating the data on landslide occurrences with those the triggering factors (provided that the historical records are sufficient for this) or through dynamic modeling.

A framework for analyzing landslide hazard analysis proposed for Hong Kong based on landslide records through the use of GIS technology. Using GIS and other technologies could provide a unique opportunity to cope with old problems, such as the control of natural disasters. This is because the collection, manipulation and analysis of the environmental data can be much more efficiently and cost-effectively accomplished by applying GIS techniques, which also greatly facilitate the use of the same data set for different types of hazard.

Rainfall and high slope are two crucial parameters to be predicted accurately in order to study potential risk of landslide and provide and warnings to people who lived in area expected to be affected by landslide. Furthermore, the integration of landslide risk assessment with city planning will provide a tremendous help to officials to take their decision when a disaster occurred.

References

Cruden DM, Varnes DJ. 1996. Landslide Types and Processes. In Landslides: Investigation and Mitigation, Turner AK, Schuster RL (eds.). National Academy Press: Washington DC; 36-75.

Coussot, P., and Meunier, M. 1996. Recognition, classification and mechanical description of debris flows. Earth-Science Review, 40, 209-227.

Chau, K.T., Wong, R.H.C., Lui, J., Lee, C.F., 2003. Rockfall hazard analysis for Hong Kong based on rock fall inventory Rock Mechanics and Rock Engineering 36 (5), 383–408

Dikau R, Brunsden D, Schrott L, Ibsen M. (eds.) 1996. Landslide Recognition: Identification, Movement and Causes. Wiley: Chichester.

Fell, R., 1994, Landslide risk assessment and acceptable risk, Canadian Geotechnical Journal, 31, 261-272.

Guzzetti F., Carrara A., Cardinali M. & Reichenbach P., 1999, Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. – Geomor., 31, 181-216.

Hansen, A., 1984. Landslide hazard analysis. In: Brunsden, D.,Prior, D.B. (Eds.), Slope Instability. Wiley, New York, pp. 523–602.

Hutchinson JN, 1995, Landslide hazard assessment. In: Proc VI Int Symp on Landslides, Christchurch, 1:1805-1842.

Hungr O, Evans SG, Bovis M, and Hutchinson JN (2001) Review of the classification of landslides of the flow type. Environmental and Engineering Geoscience, VII, 221-238.

Leroi, E., 1997. Landslide Risk Mapping: Problems, Limitation and Developments. In: Cruden, Fell, (Eds.), Landslide Risk Assessment. Balkema, Rotterdam, pp. 239–250.

Leroi E., Bonnard Ch., Fell R., McInnes R., 2005, Risk assessment and management, Landslide Risk Management, 159-198.

Maquaire O., Malet J.-P., 2006, Shallow landsliding. In Boardman, J. & Poesen, J. (eds): Soil erosion in Europe, Wiley, London, 583-598.

Picarelli L. 2001. Transition from slide to earthflow and the reverse. In Transition from Slide to Flow. echanisms and Remedial Measures, Sassa K (ed.). Pàtron Editore: Bologna; 21-54.

Varnes DJ. 1978. Slope Movement Types and Processes. In Landslides: Analysis and Control,Schuster RL.

Van Driel, N.: 1991, Geographical Information Systems for Earth Science Applications, Proc. IV Int.Conf. on Seismic Zonation, Stanford, Aug. 25–29, 1991, Vol. 1, pp. 469–485.

Van Beek R (2002) Assessment of the influence of changes in climate and land use on landslide activity in a Mediterranean environment. Netherlands Geographical Studies no. 294, KNAG, Faculty of Geosciences, Utrecht University,p 366.

Van Westen, C. J., Van Asch, T.W.J. and Soeters, R. (2006). Landslide hazard and risk zonation – why is still so difficult? Bulletin of Engineering Geology and the Environment, 65: 167-184

Appendices:

A: The paper used for Hong Kong landslide case study
B: CD of Power Point presentation of GIS Application on Landslide Hazard Analysis
C: Paper of land slide and processes