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Remote Sensing Applications
P. S. Roy
R. S. Dwivedi
D. Vijayan
इसरो isro
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National Remote Sensing Centre

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Landslides

14.1. Introduction

A frequently used definition of landslide is “a movement of mass of rock, earth or debris down a slope” (Cruden, 1991). They can occur on many types of terrain given the right conditions of soil, rock, moisture condition and slope. Integral to the natural process of the earth’s surface geology, landslides serve to redistribute soil and sediments in a process that can be in abrupt collapses or in slow gradual slides. Classification of landslides was first formally proposed by Varnes (1978) based on types of movement and types of material. A landslide can be classified and described by two nouns; the first describes the material and the second describes the movement. The material can be rock, debris and earth or a mix. The movement can be fall, topple, slide, spread and flow. Hence, a landslide can be named as rock fall (‘rock’ is the material type + ‘fall’ is the movement type), debris flow and so on. It is recommended to use a combination of one/two of these nouns to describe a landslide, though in nature, we notice a mix of materials and movements and then we are tempted to use the term ‘complex landslide’, which normally should be avoided. The features and geometry of a landslide is explained in figure 14.1. Details of various landslide types and processes can be found in Cruden and Varnes (1996).

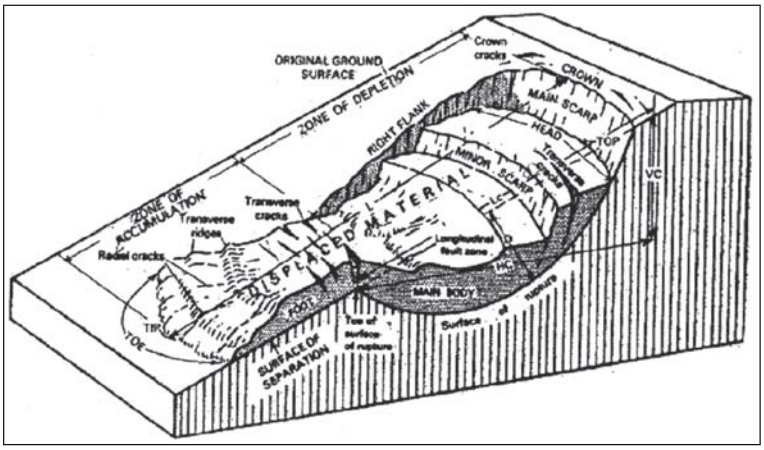

Figure 14.1: Block diagram of a landslide (source: Varnes, 1976)

Zonation refers to “the division of the land into homogenous areas or domains and their ranking according to degree of actual/potential hazard caused by mass movement” (Varnes, 1984). Landslide Hazard Zonation (LHZ) is defined as the “mapping of areas with an equal probability of occurrence of landslides of a given type and magnitude within a specified period of time” (Guzzetti *et al.*, 1999; Varnes, 1984). Landslide hazard is commonly shown on maps as areas or zones, which display the spatial distribution of landslide hazard classes. To do this, the fundamental steps are the spatial prediction of susceptible zones, estimation on the probability of magnitude of future landslide and then temporal prediction of landslide recurrence in different susceptible zones. Landslide hazard estimates in turn, are the most crucial input to risk analysis, the latter being defined as “the expected number of lives lost, persons injured and damage to property and disruption of economic activity due to a particular landslide hazard phenomenon for a given area and reference period” (Varnes, 1984).

14.1.1. Cause of Landslide

The terrain factors such as slope, lithology, geological structure, land use, lineament density, geomorphology etc., are important for a landslide to occur in an area. If terrain factors are favourable e.g., high lineament density, unconsolidated rock, steep slope etc., then the area is susceptible to landslide. Landslides can be triggered by rainfall, undercutting of slopes due to flooding or excavation, earthquakes, snowmelt and other natural causes as well as human-made causes, such as over grazing by cattle, terrain cutting and filling and excessive development. Rainfall increases the pore water pressure. So the shear strength of the rock decreases. This leads to landslide in an area. In India, most of the landslides occur during rainy season due to heavy downpour in a short time.

14.1.2. Role of remote sensing in Landslide Inventory

Comprehensive landslide inventory is a prerequisite for landslide hazard and risk analysis. A landslide inventory map not only shows the time and date of occurrence but also the types of landslide. Landslide inventories can make use of a variety of approaches, ranging from digital stereo image interpretation to automatic classification based either on spectral or altitude differences, or a combination of both. The multi temporal images can be used to prepare a landslide activity map. The stereo-images are not only useful for the derivation of height information but also for landslide inventory mapping as it provides a 3-dimensional visualisation opportunity (Vinod Kumar *et* *al.*, 2006, 2008). Updation of landslide inventory map after earthquake / rainfall can be done with satellite data (Vinod Kumar *et al.*, 2006).

Very high resolution imagery (QuickBird, IKONOS, CARTOSAT-1 and 2) has become the best option now for landslide mapping, and the number of operational sensors with similar characteristics is growing year by year (van Westen *et al.*, 2007). Other remote sensing approaches of landslide inventory mapping include shaded relief images produced from Light Detection and Ranging (LiDAR) DEM and Synthetic Aperture Radar (SAR) interferometry. Lidar is an active sensor and the signal from the sensor from onboard aircraft has the capability of penetrating through the tree crown (most of the times) and thus provides data about subtle elevation variation of the bare ground. Lidar data have been used even to prepare landslide inventory under forest areas in hilly regions and to refine the boundaries of landslides prepared during field investigations. This data is not only useful for mapping old landslides but also can improve field survey based investigation in regions with subdued morphology (Van Den Eeckhaut *et al.*, 2007). SAR images are useful in identifying critical terrain elements such as faults and slope characteristics. Also subtle movement due to landslides can be picked up from interferograms generated from SAR images. Another advantage of SAR data over optical sensor data is its all weather monitoring ability. So, combination of SAR imagery with high resolution optical multispectral is useful for monitoring debris hazard in mountainous areas (Tsutsui *et al.*, 2004). However the problems such as foreshortening and layover effects associated with SAR data in mountainous areas have to be addressed carefully.

14.2. Global and National Scenario

Landslides are among the main natural catastrophes, which have caused major problems in mountainous terrain by killing hundreds of people every year besides damaging property and blocking transportation links. In some areas, such as the western coastal parts of North and South America, Central America, Alpine regions of Italy, France, Switzerland and Austria in Europe, Himalayan regions of India, Nepal in Asia and parts Central Asia, the effects of landslides are more pronounced mainly due to the spurred developmental activities to meet the ever growing demand of people. As per the official figures of United Nations International Strategy for Disaster Reduction (UN/ISDR) and the Centre for Research on the Epidemiology of Disasters (CRED) for the year 2006, landslide ranked 3rd in terms of number of deaths among the top ten natural disasters. Approximately 4 millions people were affected by landslides in 2006 (OFDA/CRED, 2006). Regions with the highest landslide risk are found in Colombia, Tajikistan, India, and Nepal where the estimated number of people killed per year per 100 km^2 was found to be greater than one (Nadim *et al.*, 2006).

Incidences of landslides are not uncommon in India. Approximately 0.49 million km^2 or 15% of land area of the country is vulnerable to landslide hazard. Out of this, 0.098 million km^2 is located in north eastern region and rest 80% is spread over Himalayas, Nilgiris, Ranchi Plateau and Eastern and Western Ghats (GSI, 2006). The states of Uttarakhand, Himachal pradesh have been facing landslide problems for a long time. Some of the big landslides of Uttarakhand in recent years are Vishnuprayag, Baldora, Lambaghar Chatti, Jharkula, Phata Byung landslides and Amiya landslide. One of the major landslides in the recent history of India is the 1998 Malpa landslide in which 221 persons were killed. Hence, there is an urgent need to formulate strategies for minimising the societal impact of landslides. One of the first steps in this direction is the preparation of Landslide Hazard Zonation (LHZ)/susceptibility and landslide risk maps and making them available to the concerned governmental as well as non-governmental/local bodies for taking up necessary actions.

14.3. Methods of Landslide Hazard Zonation (LHZ)

14.3.1. Conventional method

Conventional methods of landslide investigation are the most accurate as it focus on a small area and relies on extensive field investigations. In this method, an expert visits the area and based on his/her knowledge about the geology, geomorphology of the area, assigns a susceptibility class of landslide to it. But it has a serious limitation as it is labour intensive and it is also impossible to carry out this method of hazard zonation for large country like India.

14.3.2. Statistical method

Landslide susceptibility can be determined through deterministic method, which is followed in smaller areas on larger scales (larger than 1:10000). These methods are process-based and give more detailed results, expressing the hazard in terms of factor of safety to each mapping unit. The deterministic method can quantitatively represent the landsliding processes by considering the detailed physical and dynamic in-situ parameters of slope forming material and can easily be used to retrieve temporal probability information by modeling different groundwater scenarios caused by different rainfall event (triggering factor). The deterministic methods highly depend on a large number of detailed site-specific geotechnical and groundwater parameters, otherwise its results are oversimplified (Moon and Blackstock, 2004) and that is why for medium scale (1:25,000 to 1:50,000) analysis in a large area, the use of such deterministic method may not be feasible. Deterministic models are also difficult to represent as 2D GIS spatial data product because it considers depth wise data variability for calculation of factor of safety. That is why for hazard assessment of bigger areas on medium scale, empirical methods based on various statistical and mathematical techniques are followed.

In medium scale landslide susceptibility analysis, knowledge-driven/ heuristic and data-driven empirical methods are prevalent. The knowledge-driven methods are mostly qualitative (direct) but semi-quantitative methods (indirect) based on heuristics are also followed. The data-driven methods are mostly statistical (bivariate and multivariate) and few are mathematical (artificial neural network).

The knowledge-driven/heuristic direct approaches to spatial prediction of landslide susceptibility involve detailed geomorphological mapping using uniquely coded polygons, which are evaluated one-by-one by an expert to assess the type and degree of hazard (Barredo *et al.*, 2000; Hansen, 1984; Varnes, 1984). Indirect heuristic approach utilizes data integration techniques, including qualitative parameter combination, in which the analyst assigns weighting values to a series of terrain parameters and to each class within each parameter**.** The relative importance of each terrain parameter as a predisposing determining factor of slope instability is quantitatively determined by pair-wise comparison using the so-called analytical hierarchy process (AHP) (Saaty, 1996) or is incorporated through spatial multi-criteria evaluation (SMCE). In direct heuristic methods, use of detailed geomorphological factor maps in general raised the overall accuracy of the susceptibility maps**,** though the accuracy of such direct qualitative model largely depends on the experience of the expert using the method. Whereas, in indirect heuristic methods, similar weight values are considered for all locations within the same factor. The addition of such unique weight values tends to “flatten out” the results of indirect methods. Thus, the main limitations of the knowledge-driven methods are the subjectivity involved both in the direct mapping as well as in the assignment of weights in indirect methods and general non-availability of any quantitative technique of model validation.

Since the late eighties, the increasing popularity of geographic information system (GIS) has facilitated development of various *quantitative or data-dependent* landslide spatial prediction methods (Aleotti and Chowdhury, 1999). GIS is very suitable for such methods, in which all possible landslide contributing terrain geofactors (evidence) are combined with landslide inventory map (target) using data-integration techniques (Bonham-Carter, 1996; Chung *et al.*, 1995; van Westen, 1993). Thus, in such quantitative methods of hazard estimation, spatial associations of past and present landslides and associated geofactors act as the key parameters to predict future landslides (Carrara *et al.*, 1991; Zezere *et al.*, 2004). These data-dependent methods aim to introduce objectivity in analysis by reducing subjectivity or generalisation of the true knowledge-driven methods.

Amongst the quantitative methods, the application of the *bivariate statistics* (e.g., weight of evidence method) in landslide spatial prediction is common and it needs to be weighed in light of following limitations because of mis-applications by many researchers, which include i) generalisation by assuming that landslides happen under the same combination of factors throughout the study area, ii) ignorance of the fact that each landslide type has its own set of causal factors, and should be analysed individually and iii) lack of suitable expert opinion on different landslide types and processes and of slides of different periods, which may be inevitable if these methods are solely applied by GIS-experts, and not by earth scientists (Westen *et al.*, 2003). Another debate regarding bivariate methods is that, instead of partitioning the study area into unique domains or mapping/ terrain/ slope unit, the conditional probabilities are determined for separate geofactors and then added sequentially under the assumption that such factors are weakly correlated to each other (assumption of conditional independence amongst independent variables). It has been argued by some researchers (Carrara *et al.*, 1995) that this method perhaps holds true where very few environmental factors are only responsible for landslides, and a sound expert knowledge exists about the landslide processes.

Bivariate or multivariate methods may be found statistically suitable to predict future landslides at medium scales (1:25,000 to 1:50,000), but logical explanations of the results or outputs and exact knowledge about the dependencies of causal parameters with the target are sometimes absent in these type of methods. Since these methods are mostly based on various statistical data treatments focused mainly for objective elimination or reduction of errors and uncertainty in prediction, the aspects of data quality, reasoned selection of input parameters and inherent fuzziness of some geofactor data etc., are frequently overlooked. Multivariate methods, in spite of limitations and pitfalls in applications, are used nowadays as among the most feasible quantitative tools for assessing different levels of landslide susceptibility. For example, when a set of independent variables include both good and bad predictors (the latter having no clear physical relationship with mass movement processes), a step wise regression technique in multivariate statistics is followed with an aim to eliminate statistically non-significant factors, but sometimes the output of these analyses may generate unreliable and meaningless results. In similar way, artificial neural network (ANN) – a mathematical technique is also used for spatial prediction of landslide hazard. The ANN method is not sensitive to any statistical distribution of data, and can integrate both continuous as well as categorical data set. The ANN methods are adaptive and generic in nature. They are construed to handle imperfect or incomplete datasets and can capture non-linear and complex interactions among variables of a system (Lee *et al.*, 2003). Since ANN is almost independent of the quality of input variable; chances of getting unreasonable goodness in results are sometimes highly abstract and misleading. Like multivariate techniques, in ANN method also, the internal processes which train the input dataset and minimise the statistical errors and uncertainties are difficult to follow.

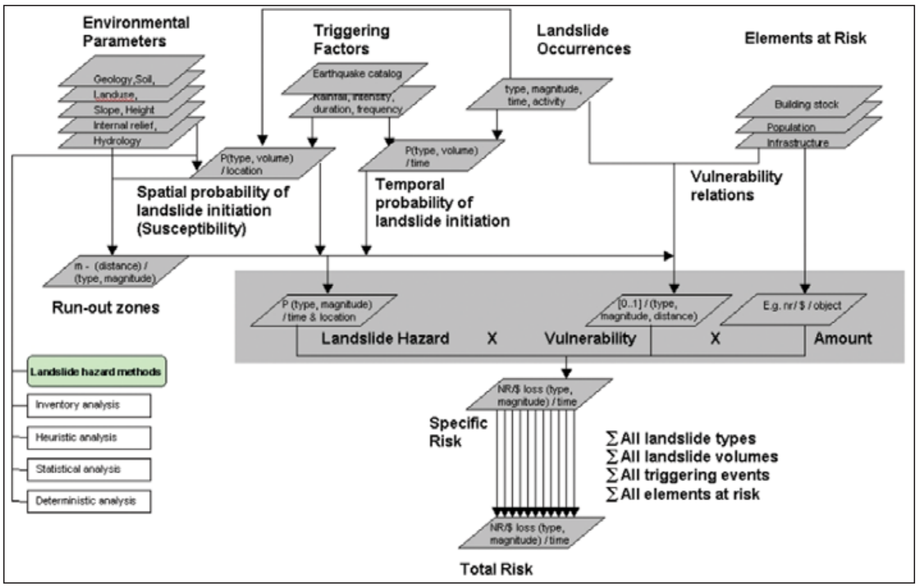

Figure 14.2: A generalised flowchart for LHZ and landslide risk mapping (source: van Westen et al., 2008)

Landslide risk mapping is a step forward to hazard zonation. The elements at risk and the vulnerability of these elements to a landslide are the key factors to calculate the landslide risk. Figure 14.2 shows the general methodology for landslide hazard and risk mapping.

14.4. Gap Areas

Understanding of the processes that lead to landslide is very crucial to any successful landslide hazard zonation. Landslide is an active field of research. The methodology of landslide hazard zonation mapping is changing with availability of new datasets and tools.

In order to prepare an accurate landslide susceptibility map, it is important to know the terrain factors favourable for landslide. Instead of considering all the factors, research is required to find out the critical factors of the landslide susceptibility mapping.

Determination of temporal probability of landslides in given set of terrain condition is required to prepare the landslide hazard map from the landslide susceptibility map. Normally it is done by calculating the return period of landslide using rainfall data, which is a common triggering factor for landslides. It is a difficult task as we require historical rainfall, which in most cases is not available. Research is required to calculate of return period of the landslide not only due to rainfall but also due to earthquake and snowmelt, which can be integrated with the landslide susceptibility map.

As we know, the areas under high landslide hazard category may not be always at high risk. Elements at risk and calculation of vulnerability are important factors for preparation of landslide risk map, which are often difficult to determine. Finally we need to have proper policies and laws where these maps prepared can be implemented on the ground so that life and property can be saved.

14.5. Major Application Projects

The following major landslide projects are carried out by NRSC.

14.5.1. LHZ mapping in Uttarakhand and Himachal Pradesh

Landslide hazard zonation (LHZ) map for important pilgrimage/tourist routes covering 2000 km road length for the states of Uttarakhand and Himachal Pradesh are prepared using satellite data and GIS. This project was carried out in association with other scientific organisations such as CBRI, WIHG. Total 14 thematic layers such as lithology, geomorphology, geological structure, and slope are prepared and integrated in GIS to prepare the landslide hazard maps. Figure 14.3 shows the landslide susceptibility map prepared for Uttarkashi. These maps are prepared in the year 2001 on 1:25 000 scale and two Atlases are published separately for both the states. Subsequently theses maps are validated using the landslides that have occurred after 2001.

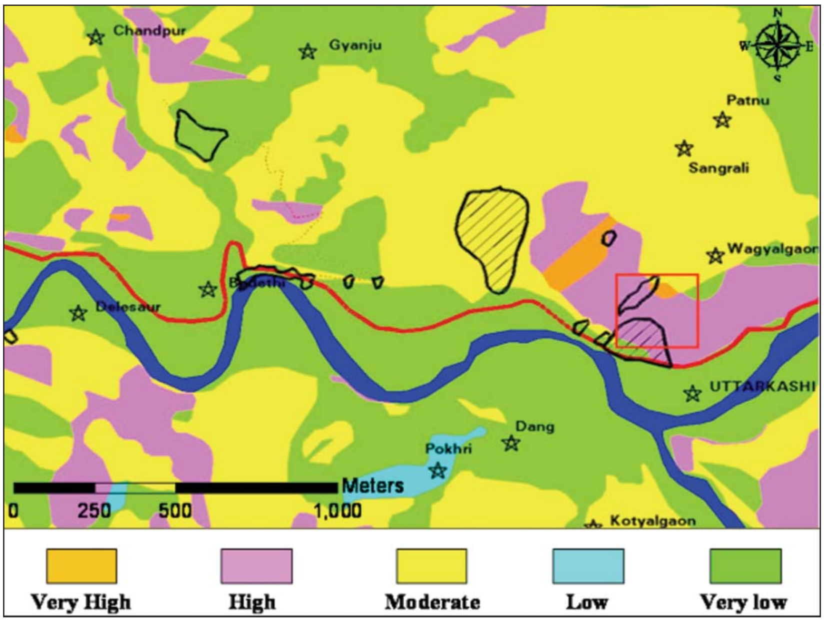

Figure 14.3: Landslide susceptibility map of Uttarkashi and its surrounding, Uttarakhand prepared using remote sensing data and GIS analysis

14.5.2. Mumbai – Goa (NH-17) Route

This project is being carried out in association with Geological Survey of India (GSI). The objective of this project is to prepare landslide hazard zonation map on 1:50,000 scale. This project is of similar nature to the previous project. The types of landslides are different in this area from the Himalayas. Mostly they are shallow translational landslides. They are controlled by the depth of the soil cover.

14.5.3. Varunawat Landslide

The town of Uttarkashi is situated on the foothill of Varunawat Parbat. It is on the right bank of Bhagirathi river in the Uttarakhand. Himalaya witnessed a serious landslide crisis, which started on 23 September 2003 and continued for two weeks, but the situation became grave by 1 October 2003. Severe damage was caused to the residential areas and infrastructure facilities such as power sub-station and the Rishikesh–Gangotri national highway around the small township of Uttarkashi. Fortunately, there was no loss of human and animal lives due to the timely and combined efforts of the local administration in warning and evacuating the people.

A detail study was carried out using aerial photographs acquired by NRSC after the landslide. The objective was to find out the cause of the landslide. The landslide map is prepared on 1:10,000 scale, which can be used for post landslide management measures (Vinod Kumar *et al.*, 2008).

14.5.4. DSC Activity

Landslide is identified as one of the disasters in the DMSP programme of ISRO. As a part of this activity, every year landslides are monitored using the high resolution Indian satellite data in Decision Support Centre (DSC) at NRSC.

14.6. Methods to solve problem

Similar to other geo-hazards, landslide can not be avoided in mountainous terrain. Better understanding of this hazard will help people to live in harmony with the pristine nature.

Since India has 15% of its land area prone to landslides, preparation of LHZ maps for these areas is of paramount importance for prioritising the areas critical to landslides. These LHZ maps will also be an important input for preparing the landslide management maps. Ministry of Home Affairs, Government of India has identified GSI as the nodal office to prepare landslide hazard map on 1:50,000 scale for the vulnerable areas of India in association with Survey of India and NRSC. These maps will act as guideline for the developmental activities such as road, dam, building construction in the mountainous areas.

Big landslides are a perennial problem by blocking transportation routes should be treated geotechnically on the ground. The methods that are normally practiced for such purpose are explained below.

- Minimising the infiltration of rain /surface water into the slide zones
- Channelisation of water in the crown portion by constructing line horizontal gravity drains drilled either from the slope surface or from drainage wells or galleries
- Modifying / resloping unstable weathered material in the crown portion
- The scarp portions where the fragmented and fractured rocks are exposed can be reinforced through anchoring of rocks
- Removal of the roots of trees growing in cracks and grouting the natural fracture zones in the primary zones of accumulation
- In order to stabilise the loose soil debris, soil nailing can be used to stabilise the potentially stable slopes where the creeping process is in progress
- In order to minimise the hazard of rock-fall the best process is to let the fall occur and to control their distance and direction of travel. This includes catchments ditches and barriers, wire mesh fences and rock sheds at the toe of slope
- Proper measurements to prevent forest fire in the slide-affected areas
- Retention wall, terracing is useful as it modifies the slope

14.7. Monitoring of Landslides

Monitoring of landslides can be carried out on two scales; one for the regional scale using remote sensing data and the other for specific sites using ground instruments.

14.7.1. Remote sensing

Satellites have a limitation on the frequency of observation. So they are used to find out the changes in terms of number of landslides over a period of time. High resolution satellite data are very helpful for this purpose. Though there are limitations of satellite remote sensing for site specific monitoring due to poor revisit period, terrestrial remote sensing techniques using SAR interferometry, terrestrial laser scanner are emerging as alternate tools. These methods are very precise and can predict movement with centimeter level of accuracy. Terrestrial laser scanner can observe continuously the change in the density of joint density pattern and indicate the areas of new stress built up.

14.7.2. Ground instruments

Ground instruments in the landslide prone areas are used to measure parameters such as surface and sub surface movements, surface and sub-surface water movement. From site specific monitoring, we can get a real time data and then fit a slope stability model and then predict the time of occurrence of a landslide. Though the correct predication of occurrence of landslides is uncommon, it happened once in China, when a landslide in the year 1995 was predicted one day ahead

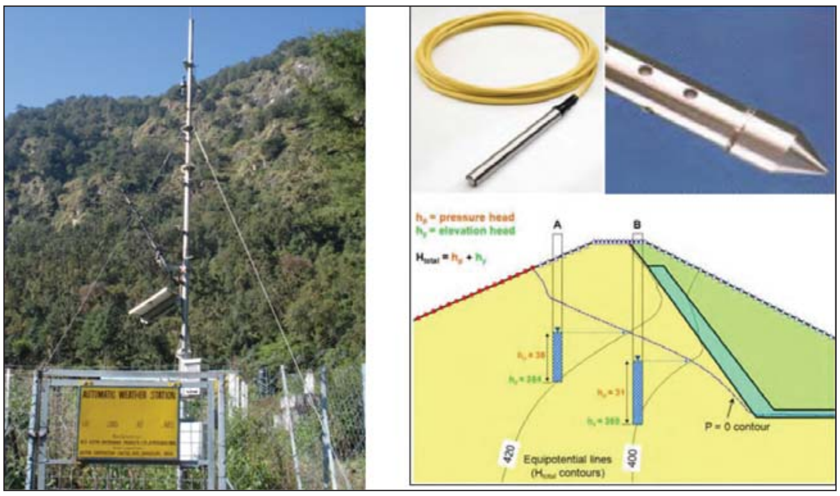

Figure 14.4: (a) AWS of ISRO near Kandi landslide, Uttarakhand and 4(b) Piezometer

along the Yellow river. Success of site specific monitoring may lead to a landslide early warning, which will save people and property. Instruments useful for site specific monitoring of landslides are GPS, piezometer (figure 14.4(b)), raingauge, extensometer, inclinometer, tiltmeter, automatic weather station (AWS) in figure 14.4(a). AWS is useful in measuring rainfall, humidity, windspeed, etc.

14.8. Cost benefit analysis

Previously aerial photo interpretation (API) was used extensively to prepare landslide inventories. But now with the availability of high resolution imageries, the focus has shifted away from the aerial photographs. A cost comparison between aerial photos and IKONOS image, carried out by Nichol *et al.*, (2006) shows that, if air photos have already been taken and are available, the overall cost of the air-photo-based approach is similar to that of the IKONOS-based approach. If flying costs to take new air photos are added, the cost of the air-photo-based approach becomes 46% higher or 41% higher if tasking of IKONOS is required.

Use of remote sensing data in conjunction with field investigation is a cost effective method for landslide studies. Again, landslide mostly occurs in inaccessible areas, where it is difficult to carry out field investigations. Now with the lowering of the prices of some satellite data and free availability of some satellite data such as Landsat TM/ETM+ and SRTM DEM, the cost of such studies has further reduced.

14.9. Summary

The physical processes that lead to a landslide are very important for successful landslide hazard zonation of an area. Satellite remote sensing data is now exetensively used for preparation of thematic layers. DEM derived from satellite data will now provide important parameters such as slope but also help in better geovisualisation. Moreover, GIS has contributed substantially to the processes of making spatial analyses of landslides.

However, we know very much less about how non-scientists, including public administrators, view the landslide hazard. As mentioned by Alexander (2008), there is a disjuncture between the ability to understand, on the one hand which slopes will fail, as well as when and how that will happen, and, on the other hand, why the public seems to find it so hard to recognise and avoid situations of slope failure hazard.

Earth scientists are vigorously responding to the technical challenge of coupling GIS, remote sensing and slope monitoring systems to yield accurate, timely information on landslide hazard (Soeters and Westen, 1996). But at the same time we must listen to the concerns of public safety officials and providing information of a kind that is useful to them.

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