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ENGINEERING GUIDELINES ON LANDSLIDE MITIGATION MEASURES FOR INDIAN ROADS

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ENGINEERING GUIDELINES ON LANDSLIDE MITIGATION MEASURES FOR INDIAN ROADS

DEFINITION

Abandoned: Inactive landslide no longer affected by its original causes.

Acceptable Risk – A risk for which, for the purposes of life or work, we are prepared to accept as it is with no regard to its management. Society does not generally consider expenditure in further reducing such risks justifiable.

Accumulated Mass; Accumulation: Volume of displaced material that lies above the original ground surface of a landslide.

Active: Landslide that is currently moving, first-time movement or reactivated.

Activity: Stage of development of a landslide, including the state of activity, distribution of activity, and style of activity.

Advancing: Activity the rupture surface extends in the direction of movement.

ALARP: As Low as Reasonably Practicable; with reference to risk.

Analysis: Process to determine the nature and level of hazard and risk; typically includes scope definition, identification and estimation.

Annual Exceedance Probability (AEP) – The estimated probability that an event of specified magnitude will be exceeded in any year.s

Assessment: Overall process of hazard or risk identification, analysis and evaluation.

Complex: Activity where a landslide exhibits at least two types of movement (fall, topple, slide, spread, or flow) in sequence.

Composite: Activity where a landslide exhibits at least two types of movement (fall, topple, slide, spread, or flow) in different parts of the displaced mass at the same time.

Confining: Activity where there is a scarp but no rupture surface visible at the foot of the displaced mass.

Consequence: Probability of total loss or damage, or a proportion of loss or damage, to an element at risk; combination of spatial probability, temporal probability and vulnerability.

Control: Process of decision making for managing hazard or risk, and implementation or enforcement of hazard or risk mitigation measures and re-evaluation of the effectiveness from time to time, using the results of hazard of risk assessment as one input.

Criteria: Terms of reference against which the significance of a hazard or risk are evaluated.

Danger (Threat): Natural phenomenon that could lead to loss, disadvantage, damage, injury or loss of life; does not include any forecasting; also see Hazard.

Disaster: A serious disruption of the functioning of society, causing widespread human, material or environmental losses, which exceed the ability of affected society to cope using only its own resources.

Dormant: Inactive landslide that can be reactivated by its original or other causes.

Early Warning: Provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response.

Elements at Risk: population, buildings and engineering works, economic activities, public utilities, other infrastructure, and environmental values in an area affected, or potentially affected by a landslide.

Enlarging: Activity where the rupture surface of a landslide is extending in two or more directions.

Erosion: Process of weathering and transport of soil and rock from their natural environment or source. Agents of erosion include wind, water, ice, gravity and living organisms (bioerosion).

Estimation: The determination of hazard or risk.

Evaluation: Using values and judgments in the decision process, either explicitly or implicitly, to determine the importance of the estimated hazard or risks, and there by identify alternatives to manage the hazards or risks.

Event: Occurrence or change of a particular set of circumstances; a landslide is an example of an event.

Frequency: Probability or likelihood of occurrence of a repeating event, such as a landslide, expressed as the number of occurrences per unit time; also a measure of past occurrences per unit time; also see Probability and Likelihood.

Hazard: Condition with the potential for causing an undesirable consequence; source of potential harm; also see Danger; or

Inactive: Landslide that has not moved within the last 12 months; can be sub-divided into dormant, abandoned, stabilized, relict, and repaired.

Individual Risk: Risk of the fatality or injury to an identifiable individual who lives or otherwise occupies an area affected, or potentially affected, by a landslide.

Intensity: Set of spatially distributed parameters related to the destructive power of landslide; can be described quantitatively or qualitatively; can include maximum velocity, total displacement, differential displacement, depth of moving mass, peak discharge per unit width, kinetic energy per unit area.

Inventory: Study of the location, classification, volume, activity, date of occurrence and other characteristics of landslide within an area.

Involuntary Risk: Risk that typically is imposed on an individual or society.

Landslide: Down slope movement of a mass of soil (earth or debris) or rock down a slope.

Level of Hazard or Risk: Magnitude of a hazard or risk, expressed in terms of probability or likelihood (for hazard) and in terms of probability or likelihood and consequences (for risk).

Likelihood: Chance of an event occurring; a qualitative description of probability of a landslide.

Management: Process of hazard or risk assessment and control or treatment.

Marginal: Inactive landslide, between preparatory and active, where a trigger can initiate movement.

Mitigation: Strategy to reduce the effect of a landslide.

Monitoring: Continual or frequent checking, critically observing or determining the status of activity of a landslide to identify change.

Multiple: Activity where a landslide shows repeated development of the same type of movement.

Partial Risk: Combination of the probability of a (hazardous) landslide and probability of the landslide affecting the site of an element at risk at the site when the landslide occurs; does not consider vulnerability; P(HA) = P(S:H) x P(T:S).

Passive: From of mitigation that requires no design engineering; includes avoidance, land use regulations, education and warning systems.

Preparatory: Inactive land area where destabilizing processes are insufficient to cause a landslide.

Preparatory Causes: Reasons(s) that a landslide occurred at a particular location and time; mechanism(s) that put a landslide into a preparatory state of activity; can include geological factors (e.g. sensitive material, joints and fissures), geomorphological factors (e.g. slope angle, erosion), physical factors (e.g. rainfall, earthquake) and factors associated with human activity (e.g. addition of a load or excavation).s

Probability:

a) Estimate of the degree of certainty between 0 (impossible) and 1 (certain) of an event occurring; also see Likelihood and Frequency; can be statistical or subjective; or

b) Probability of occurrence of a landslide; can be statistical or subjective; P(H).

Qualitative Risk Analysis: Analysis that uses descriptive words or numeric rating scales to describe likelihood, vulnerability and consequences.

Quantitative Risk Analysis: Analysis based on numerical values of probability, vulnerability and consequences.

Reactivated: Landslide that is again active after being inactive.

Rapid: Slope movement with velocity greater than 1.8 m/hour (0.5 mm/sec).

Relict: Inactive landslide that developed under climatic or geomorphological conditions considerably different from those at present.

Remediation: Strategy by which the effects of a landslide are reduced.

Repaired: Inactive landslide that has been temporarily protected from its original cause(s) by artificial remedial measures.

Retrogressing: Activity where the surface of rupture extends in the direction opposite to the movement of the displaced material.

Residual: Hazard or risk remaining after mitigation.

Risk: A measure of the probability and severity of an adverse effect to individuals or populations, property or the environment.

Run-Out: Maximum travel distance of a landslide.

Run- Up: Maximum height reached by a landslide mass.

Single: Activity where a landslide exhibits only one type of movement (fall, topple, slide, flow, spread).

Slope Instability: The predisposition of a slope to mass movement. The condition may be recognized by analysis of stress within the slope, by various slope characteristics or by analysis of historical records of slope development.

Slope Stability Analysis: Analysis of static and dynamic stability of engineered and natural slopes of soil and rock.

Slump: A short, downslope movement of a coherent mass of loosely consolidated soil or rock; not a recommended term.

Societal Risk: Risk of the multiple injuries or fatalities, financial, environmental, and other losses from a landslide, the burden of which society has to carry.

Soil: Aggregate of solid, typically inorganic particles that either was transported or was formed in situ by weathering of rock; subdivided into earth and debris.

Spatial Probability: The potential of a landslide affecting the site of an element at risk; P(S:H).

Stabilized: Inactive landslide that has been permanently protected from its original causes by artificial remedial measures.

State of Activity: Terms that described the timing of landslide movements (active, reactivated, suspended, inactive, dormant, abandoned, stabilized, relict, preparatory, marginal, and repaired).

Style of Activity: Terms that described the manner in which different movements contribute to a landslide.

Subsidence: Vertical downward movement of the ground surface; frequently occurs in karst terrains or can be related to mining activities.

Successive: Activity where a landslide exhibits the same type of movement as a nearby, earlier landslide but does not share displaced material or a surface of rupture.

Susceptibility: Qualitative or quantitative analysis of the classification, volume, and spatial distribution of landslide that exist or potentially can occur in an area; can also include a description of the velocity and intensity of the existing or potential landslide; a time frame is explicitly not taken into account.

Suspended: Landslide that has moved within the last 12 months but is not active at present.

Temporal Probability: Probability that an element at risk is at the site when the site is affected by a landslide; P(T:S).

Tolerable Risk: Risk within a range within which society can live in order to have and secure certain benefits; a range of a risk regarded as non-negligible but needing to be kept under review and reduced further if possible.

Translational: Type of landslide that moves along a roughly planar surface with little rotation or backward tilting.

Trigger: Cause that puts a slope into a marginal state of activity leading to a landslide.

Velocity: Rate of movement of a landslide that can range from extremely slow (<16 mm/ year or 0.5 x 10-6 mm/second) to extremely rapid (>5 m/second).

Voluntary Risk: Risk that an individual or society typically takes willingly.

Vulnerability – The degree of loss to a given element or set of elements within the area affected by the landslide hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss). For property, the loss will be the value of the damage relative to the value of the property; for persons, it will be the probability that a particular life (the element at risk) will be lost, given the person(s) is affected by the landslide.

Widening: Activity where the rupture surface extends into one or both flanks of a landslide.

Zoning: Division of land into somewhat homogeneous areas or domains, and their ranking according to degrees of actual or potential landslide susceptibility, hazard or risk or applicability of certain landslide-related regulations.

INTRODUCTION

India, a country blessed with widely diverse physiographic, geological and climatological aspects, has a history of multi-hazard events like earthquakes, landslides, floods etc. Extreme weather events such as cloudbursts followed by heavy flash flood and landslides have lately become a frequent phenomena compare to the yester years. Many a times these events of hazards transform into disasters/catastrophes/calamities as happened during June 2013 in Uttarakhand. During June 16^{th}-17^{th} of 2013 heavy rain resulting in flash flood, breach of glacial lakes, heavy erosion etc. have caused wide spread damages and deaths of over 5000 innocent people. It was again realized that communication, particularly road communication is the one which is wanted most during such tragedies. Unfortunately it is the one which is also most severely effected.

The increasing pressure of urbanization due to rising population has forced humans to reach unstable slopes or make slopes unstable by their illegitimate intrusion in the territory of nature. Every year we get to hear about the incidences of landslides from some or other parts of India which cost us thousands of human lives and huge monetary losses by destruction of infrastructures and settlements. Highways which are primary surface communication means for catering all the needs of the inhabitants, tourists, pilgrims and armed forces in the border areas are among the most widely suffered infrastructure. The severity of this hazard is not obscured but still there are no guidelines regarding landslide management in the country.

These guidelines on “Management of Landslides on Indian Roads and Highways” are designed to help professional such as engineers, geotechnical engineers and geologist to have a good understanding of landslide hazard so that they can take appropriate steps at desired time to manage them in proper way. This document is compiled after comprehensive study of literature pertaining to landslides from all over the world including India. Best technical aspects suitable for Indian condition are considered. The guidelines are divided into eight chapters covering every aspect of the landslide mitigation and management strategy and to get a deep understanding of the hazard. Every aspect is described in simple language. The topics covered in the eight chapters are landslides features and geometry; classification of the phenomena; landslide hazard mapping; vulnerability and risk assessment; methods of scientific investigation of landslides; instrumentation, monitoring, forecasting and early warning of landslides; landslide risk reduction through improved planning, design and construction practices and technology for landslide prevention and remediation. These guidelines provide assistance to study landslide hazards in two situations, one when alignment is set to be constructed and second where road already exists.

The Disaster Management Committee (G-6) felt the necessity to draft this document and constituted a sub-group comprising of Dr. Kishor Kumar, Dr. P.K. Champti Ray; Ms. Minimol Korulla; Dr. Surya Prakash and Ms. Dola Roy Choudhari. The draft document prepared by the sub-group was discussed by the Committee in series of meetings. The G-6 Committee approved the draft document in its meeting held on 26^{th} May, 2014 for placing before the General Specifications & Standards Committee (GSS).

The Composition of Disaster Management Committee (G-6) is as given below:

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Kumar, Dr. Kishor	--------	Co-Convenor
Sharma, D.D.	--------	Member Secretary

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(Paul, Dr. N.C.)

Ex-Officio Members

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Honorary Treasurer, Indian Roads Congress	(Das, S.N.), Director General (Road Development), Ministry of Road Transport & Highways
Secretary General, Indian Roads Congress	Sajjan Singh Nahar

The same draft was placed before the General Specifications and Standards Committee (GSS) during its meeting held on 8th August, 2014 and GSS Committee approved this document subject to modifications in light of comments of members offered during the meeting. The Executive Committee in its meeting held on 18th August 2014 approved the same document for placing it before the Council. The IRC Council in its 203rd meeting held at New Delhi on 19th & 20th August, 2014 approved the draft of IRC:SP "Engineering Guidelines on Landslide

Mitigation Measures for Indian Roads" after taking on board the comments offered by the Members during the meeting and authorized the Convenor of GSS Committee to finalize the document for publishing.

1 OVERVIEW OF LANDSLIDE HAZARDS IN INDIA

Slope instability occurs in many parts of peninsular and extra-peninsular India and offer impacts on settlements, highway, dams, irrigation facility and other development. This has been recognised by most of the Government and Private authorities of hill state and coastal regions which has led to preparation of guidelines on landslides by a panel of specialists of the country and selected by NDMA in the year 2006-2009. These guidelines however are prepared for administrative purpose and do not include technical matters which can guide the user agencies about the stability assessment prior to allowing the development.

In India, the response to landslide hazard is still fragmented, reflecting the diverse nature of the hazard, incomplete database, jurisdictional overlaps, diverse and competing stake holders and the multi disciplinary nature of the issue.

1.1 Landslide Scenario in the Country

Landslides present a threat to life and livelihood throughout the world ranging from minor disruption to social and economic catastrophic[108]. Landslides are distributed in all geographic regions of the country not confined to the only hilly or mountainous areas but also in coastal areas and offshore too. 22 states and 2 union territory of the country are affected by landslides (**Fig 1.1**), although they differ from the scale of severity of disaster. Generally, the areas uninhabited and away from human intervention are found unaffected or less affected by such phenomena. While, the areas where human intervention increased vulnerability to landslide occurrences has also increased. As the population has increased quite rapidly over the last century, people had to venture in new areas, not inhabited earlier. These areas have not generally been considered based on their vulnerability to landslide disasters. As a result landslide occurrences in these areas have become common phenomena. These areas which have already experienced landslides are generally vulnerable to repeated recurrences. Most of the highways and roads planned and constructed without consideration of the probability of landslide recurrence have suffered due to repeated recurrence of such phenomena resulting in frequent interruption of traffic, road damage, loss of life and hardship to the commuters.

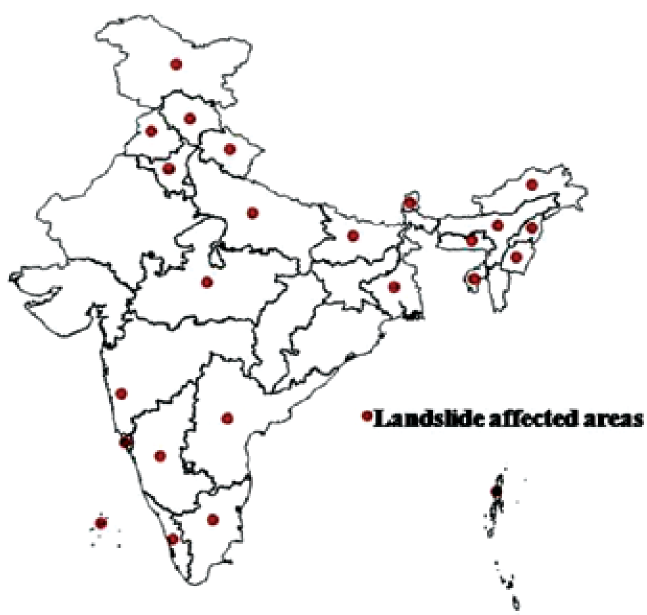

Fig 1.1 Landslide affected areas in

Every time the tragedy strikes, huge amount of budgetary funds are pumped into the rehabilitation and restoration works without giving a least thought to pre-disaster planning. By the time the tragedy stricken areas are rehabilitated, monsoon reappears again and this vicious process repeats again and again. The restoration and rehabilitation process never gets completed and an unimaginable sum of tax payers' money washes off without much fruitful results. The cost on direct losses such as the costs of repair and maintenance, restoration, rehabilitation or the replacement of the damaged properties is met out of maintenance budget allocated for the whole year excluding such exigencies; as a result, overall maintenance of the roads is also affected. The frequent and long duration blockade of national highways in critical landslide locations create social unrest amongst the communities living at both the sides of the blockade location because of their inability to attend the social obligations, hardship in reaching the destinations through the tougher and longer alternate routes, inability to provide medical aids to the critical patients, steep hike in prices of the commodities, inability to run their business etc. These scenes with series of sufferings are repeated during every monsoon.

The failure to lessen the problem, pertaining to landslides, is primarily due to the ever increasing pace of development in the terrain prone to geological hazard and failure of the respective authorities to recognise such hazards and apply appropriate methods for their prevention/mitigation even though there is a overwhelming evidence that landslide hazard mitigation purpose serve both public and private institutes by saving many times the cost of implementation.

1.2 Purpose of Guidelines

The above examples illustrate the wide distribution of the landslide and their destructive potential. Not every landslide results in catastrophic, but even small landslides have the potential to cause damage and loss of life. The proposed guidelines aim to demonstrate as how the loss of life and damage from landslide can be reduced following good practices of land use planning.

Since no new land formation can take place, we have to live with whatever we have with wise and judicious use and prevent the gradual or fast degrading land due to landslides and other mass movements by adopting certain measures and guidelines. Guidelines, particularly for the areas where planning is under progress and development is due to take place would be more important because in most of the area severity of naturally caused landslide has not increased. What has increased is the extent of human occupation of these lands and the impact of human activities on the environment.

The frequency of landslide events has got increased many folds, all over the hilly areas of the country, and there is practically not a single day when a landslide does not happen in some or other parts of the country. Recent examples of loss of life and property worth billions tell the tale of the devastation caused by landslides. Many landslide damages that have occurred might have been prevented or avoided if accurate landslide hazard information had been available and used. In order to cope with the demand of modern industrialized need of the country large number of the developmental projects for communication, highways, dams, reservoirs have been launched and are in different stages of development and many more will be launched. Planners and executors of innumerable developmental schemes should desire and demand an advance, as far as accurate and understandable information for slope instability assessment prior to execution of such developmental program. Population, living in vulnerable areas also needs adequate information about the hazard, risk and consequences of such hazard, how the local communities could be made aware of landslide hazards in their respective areas, and trained in the management of landslides to avert disasters? In view of these there is a need for guidelines for management of landslides in hill areas. However, the present guidelines are to be exclusively used for the highways/road only. The guidelines will have following purpose:

- To establish a uniform terminology and classifications of landslides
- Define a general framework for landslide management on Indian Highways-based on national and international experience.
- Provide guidance on methods which should be used to carry out the investigation, mapping, analysis and mitigation.

1.3 Whom the Guidelines

These guidelines are prepared primarily to assist the local authorities (planner) involved in the constructions and maintenance of the roads. However will also be of interest to developers, engineering geologist, geotechnical engineers who specialise in landslide hazard and risk assessment.

In case the new development the planners should be interested in early consultation with the engineering geologist and geotechnical engineers for assessment of the slope conditions prior to the development. Obviously, a planner is not expected to make technical judgement about the landslide hazard and risk, but should understand the process by which a landslide specialist provides advice. By seeking appropriate advice the planner can get information about the kind of measures and methods to prevent, minimise or avoid the negative impact of the landslides.

In case of the aleady developed area the concerned authorities, engineers should know as how to assess the hazard and associated risks from the existing landslides and what could be the best economically viable remedial measure for preventing/mitigating the impact of such hazards.

From these guidelines, the planner will gain a basic knowledge of the concepts and issues to be considered when incorporating landslide hazard information and assessment into planning process. It is envisaged that these guidelines will be regularly reviewed and updated as knowledge, technical standards and practices evolve.

The landslide guidelines a produced based on the extensive literature review from within and outside the country. A few selected guidelines of other countries have also been reviewed and used for preparation of the present document. The bibliography of the referred literature is given at the last of the document while references in the running text are avoided.

2 LANDSLIDE FEATURES AND GEOMETRY

The significance of identifying landslide features is that they provide clues on the nature of motion in the past as well as current and therefore, indicate potential hazards along the transportation routes and where protective measures are necessary.

2.1 Definition

Landslide definition has been covered widely in world literature including books and individual papers and to reproduce the same may not be worth. However, it would be appropriate to discuss the basic definition indicating the concepts of such a phenomenon before discussing the features etc. The landslide phenomenon has been defined by number of ways but the basics remain same in all.

"A landslide can be portrayed as an episode of downward and outward displacement/ movement ranging from very slow to rapid in velocity, of any kind of slope forming materials (rock, soil or their combination) under the influence of gravity."

2.2 Landslide Features

The landscape is read for signs that tell of past processes. The identification of features on the terrain or slope forms an integral part in the prediction of potential instability. Features observed in the field during mapping give direct evidence of activity/processes the slope has undergone and in a way; features can indicate whether a landslide is active or inactive, old or new etc. Recognition of these features makes it possible to identify landslides from aerial and ground inspections. Several diagnostic landslide features tell of past movement on the terrain. For example as indicated in **Fig 2.1. Fig 2.1** shows that the features which could be identified in the field directly by the working engineers before, during and after construction. Important concepts to consider include[30]:

- The un-failed slope can be termed the original ground surface.
- The mass that moves is called the displaced material. It may be intact or it may be in deformed state debris.
- The displaced mass overlies two zones: i.e. zone of depletion and zone of accumulation. The depletion zone may lie below the original ground surface

and is defined by the zone of rupture or shear plane. The accumulation zone is the area where the displaced mass lies above the surface and includes areas to which the displaced material has moved (**Figs.2.1 and 2.2**).

Ground features associated with slope instability are given in **Table 2.1 and Fig 2.3**.[30, 48]

Table 2.1 Guide to Read and Classify Landslide Features

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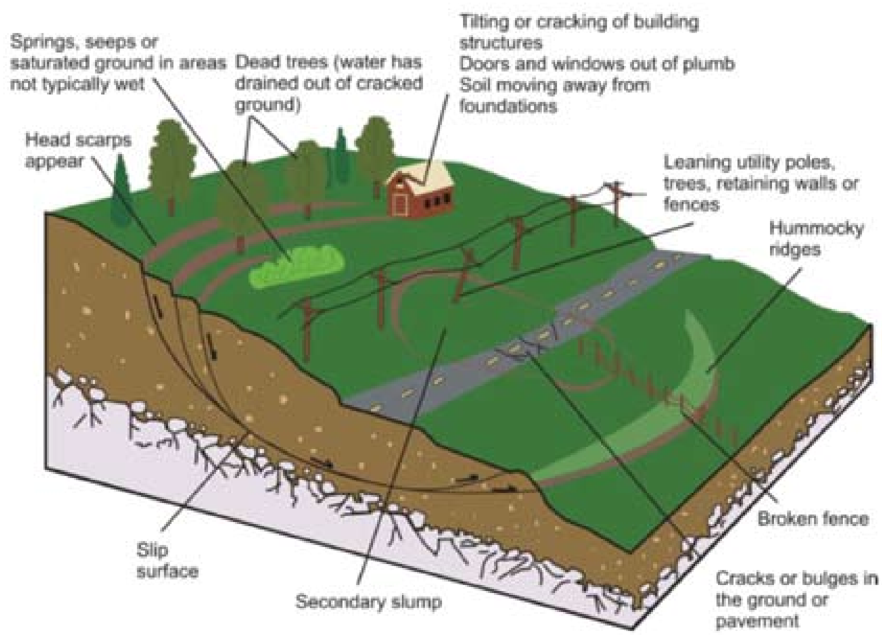

Fig. 2.3 Ground Sign of Slope Instability
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Features associated with landslides are:

extensional features like scarps
tension cracks;
shear features (shear zones)
shortening features like toes, transverse ridges and snouts

on the ground, signs of slope instability include:

Cracking
hummocky terrain
undrained crescent-shaped depressions and ponds
scarps and benches
crooked fences, trees or lamp posts leaning uphill or downhill
uneven road surfaces
swamps or wet ground in elevated positions
plants like rushes growing on a slope, and water seeping from the ground

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</table>

Some of the important notable features are indicated in **Table 2.2**.

2.2.1 *Landslide Dimension*

The quantities Ld, Wd, Dd, Lr, Wr, Dr (**Fig. 2.4 and Table 2.3**) are introduced because, with an assumption about the shape of the landslide, their products lead to estimates of the volume of the landslide that are useful in remedial work.

The volume of the slide mass is given as the product of various dimensions as:

$$Vol_{ls} = 1/6\pi D_r x W_r x L_r$$

The volume of displaced material is estimated as:

$$Vol_{ls} = 1/6\pi D_d x W_d x L_d$$

This helps in quick assessment of volume for decision making.

Table 2.2 Definitions of Landslide Features[30, 49, 54, 107, 154, 165]

Feature No.	Name	Definition
1	Crown	The practically undisplaced material still in place and adjacent to the highest parts of the main scarp.
2	Main scrap	Steep surface on undisturbed ground at the upper edge of landslide, caused by movement of displaced material (13, stippled area) away from undisturbed ground; It is visible part of surface of rupture.
3	Top	Highest point of contact between disturbed material (13) and the main scarp (2).
4	Head	Upper part of landslide along contact between displaced material and main scarp (2).
5	Minor scrap	Steep surface on displaced material of landslide produced by differential movements with displaced material.
6	Main body	Part of displaced material of landslide that overlies surface of rupture between main scarp (2) and toe of surface of rupture (11).
7	Foot	Portion of landslide that has moved beyond toe of surface of rupture (11) and overlies original ground surface (20).
8	Tip	Portion on toe (9) farthest from top (3) of land slide.
9	Toe	Lower, usually cured margin of displaced material of a landslide, most distant from the main scarp (2).
10	Surface of Rupture	Surface that forms lower boundary of displaced material (13) below original ground surface (20), mechanical idealization of surface of rupture is called slip surface.
11	Toe of surface of rupture	Intersection between lower part of surface of rupture (10) of a landslide and original ground surface (20).
12	Surface of separation	Part of original ground surface (20) now overlain by foot (7) of land slide.
13	Displaced material	Material displaced from its original position on slope by movement of landslide
14	Zone of depletion	Area of landslide with in which displaced material (13) lies below original ground surface (20).
15	Zone of accumulation	Area of landslide with in which displaced material (13) lies above original ground surface (20).
16	Depletion	Volume bounded by main scarp (2), depleted mass (17), and original ground surface (20).
17	Depleted mass	Volume of displaced material (13) that overlies surface of rupture (10) but underlies original ground surface (20).
18	Accumulation	Volume of displaced material (13) that lies above original ground surface (20).
19	Flank	Un-displaced material adjacent to the sides of surface of rupture.
20	Original ground surface	Surface of slope that existed before land slide took place.

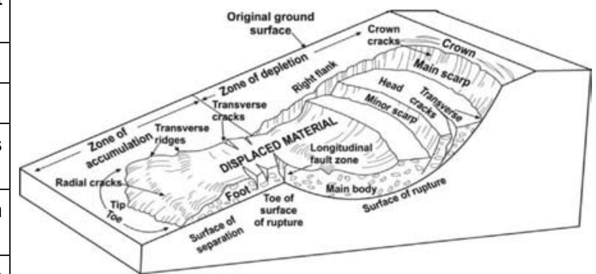


Fig. 2.1 Block Diagram of Idealized Complex Earth Slide-Earth Flow

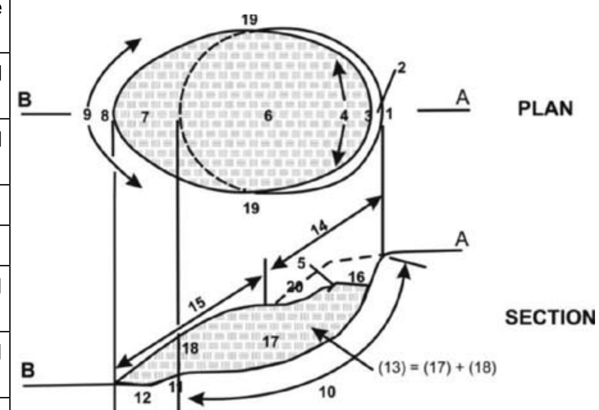


Fig. 2.2 Definition of Key Landslide Features (For Detailed Description Refer to **Table 2.1**)

Table 2.3 Dimensional Features of Landslides[165]

S. No.	Name	Definition
1	Width of displaced mass, Wd	Maximum breath of displaced mass perpendicular to the length Ld
2	Width of surface of rupture, Wr	Maximum width between flanks of landslide perpendicular to the length, Lr
3	Total length, L	Minimum distance from tip of landslide to crown
4	Length of displaced mass, Ld	Minimum distance from tip to top
5	Length of surface of rupture, Lr	Minimum distance from toe of surface of rupture to crown
6	Depth of displaced mass, Dd	Maximum depth of displaced mass measured perpendicular to plane containing Wd and Ld
7	Depth of surface of rupture, Dr	Maximum depth of displaced mass measured perpendicular to plane containing Wd and Ld
8	Length of centre line, Lcl	Distance from crown to tip of landslide through points on original ground surface equidistance from lateral margins of surface of rupture and displaced material

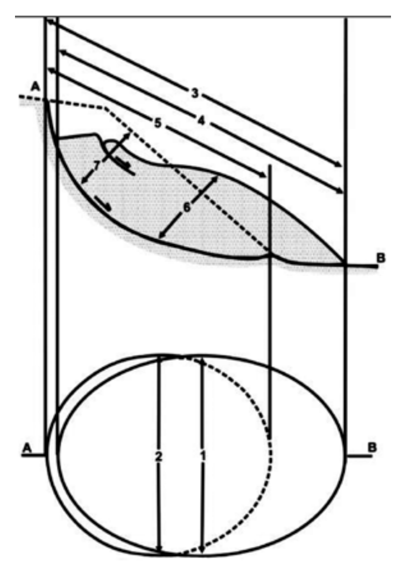


Fig. 2.4 Landslide features (Referred to Table 2.2): upper portion, plan of typical landslide in which dashed line indicates trace of rupture surface on original ground surface; lower portion section in which hatching indicates undisturbed ground and stippling shows extent of displaced material.

2.2.2 *Slope Surface Appearance*

2.2.2.1 Terrain/morphologic features indicating landslide

The features of any landslide in the field will be reflective of the type of landslide and its age[30]. For example, a rotational slide will be characterized by a steep, near vertical head scarp, gentle mid-slopes and a convex toe (Example **Fig. 3.3** of chapter classification of guidelines). A slope undergoing rock fall will have scree (or debris) at the base of the slope which can range in size from small, sand-like particles up to large boulders. Rocks or an accumulation of debris at the base of the slope indicates activity from above. Fresh activity will be characterized by sharp edges and features, as well as distinct color changes where materials have parted from the parent rock or slope. Older failures may have very degraded features included rounded head scarps and worn edges and will be reflective of the on-going weathering and erosional processes which continually modify the landscape. Diagnostic features of different types of landslides are briefly described/illustrated in many textbooks. **Table 2.4** summarizes diagnostic geomorphic features used to identify landslides & provides the significance.

Table 2.4 Field Matrix for Identifying Features of Landslide

Diagnostic Geomorphic Feature on Slope	Likely Significance of Feature with Respect to:
i) possible age and/or character of slope movement	
Fresh scars	recent or ongoing movement of part of the slope
Tension cracks, crescent-shaped or curved scarps or depressions; shallow, linear depressions: step-like benches or small scarps	recent or ongoing continuous or intermittent slope movement
Fresh rock or soil surfaces	recent or ongoing slope movement
Groups of toppled, jack-strawed, leaning, 'drunken' trees, pistol grip	recent or ongoing slope movement
Split trees	recent or ongoing differential slope movement
Disrupted roads, fences, or other linear features	recent or ongoing differential slope movement
Group of re-curved 'pistol butt' trees	recent or ongoing slow slope movement; can also indicate deep snow cover
Revegetated scars or partially revegetated strips; linear strips of even-aged vegetation or trees	older slope movement; inactive/dormant
ii) evidence/possible landslide type	
Fresh accumulation of rock or soil on lower slope or at base of step slope	rock or soil fall, topple or slide
Linear or fan shaped tracks of angular blocks below steep slopes	rock fall or debris flow
Hummocky ground, sag ponds	earth flow; can also result from erosion of displaced material of other landslide types
Rock or soil piled on the upslope side of trees	channelized debris flow
Colluvial fan or debris piles at mouth of gully	channelized debris flow
Trim lines, levees along gully; no or new vegetation in gully bottoms	channelized debris flows; levees are definitive, lack of vegetation is suggestive
Vegetation in gully much younger than the adjacent forest; poorly developed soils on gully sides relative to adjacent slopes	channelized debris flow
iii) evidence/other possible significance	
Mixed or repeated soil profiles present in natural or artificial exposures	slope movement; repeated soil profiles indicates thrusting or shearing
Buried soil profiles present in natural or artificial exposures	displaced material from landslide has buried undisturbed material
Poorly developed soils relative to other comparable slopes	possibly the result of slope movement
Terracettes across slopes	shallow slow deformation of slope; may indicate seasonally saturation or permafrost thaw
Bulging in the lower portion of a slope	incipient larger slope movement
Displaced or disrupted stream channel	slope movement into stream channel
Numerous springs along toe of slope	disruption of drainage due to slope movement

2.2.2.2 Morphological changes of landslide features with time

The geomorphic features being recorded during the field mapping portion are not all the same age. They may be currently active, inactive but young and inactive but mature. The field engineers/geologists can visualize these changes and accordingly classify the terrain as given in **Table 2.5**. This gives an understanding of the history of morphological changes with time.

Table 2.5 Description of Morphological Feature Changes with Time

Age Class	Head Scarp	Internal Morphology and Drainage	Vegetation	Toe	Estimated Absolute Age
Active	Sharp, Unvegetated	Undrained Depressions, Lakes, Hummocky Topography, Angular Internal Blocks Separated by Unvegetated Cracks	Absent or Sparse on Scarps and Internal Scarps, Tilted "jack-strawed" Trees Common	Forces Axial Drainage to Opposite Side of Valley, Dams Drainage, Covers Modern Flood Plain, Not Modified by Streams	Activity Within Historic Time, Less Than 100 years old
Inactive-Young	Sharp to Smooth, Partly Vegetated	Undrained and Drained Depressions, Ponds and Marshes, Internal Cracks Vegetated	Younger than Adjacent Terrain or Different Type or Density	Same as Above, But May be Modified by Modern Channel	100 - 5000 years old
Inactive-Mature	Smooth, Dissected, Vegetated	No Drainage Depressions, But Smooth Rolling Topography, Shear Zones Become Drainage	Same Age as Adjacent Terrain, But May be Different Density	Cut by Modern Flood Plain, Stream Not Constricted	5000 - 10,000 years old

The identification of features makes it easy to understand the terrain, type of denudational processes including landslides and also the probability of the terrain to be affected by like processes after construction of roads, based on which one can plan a strategy for type of survey, mapping, investigation etc, for selecting an alignment/correcting the new one/ landslide mitigation etc.

3 CLASSIFICATION

Since the type of landslide will determine the potential speed of movement, likely volume of displacement, distance of run-out, as well as the possible effects of the landslide and the appropriate mitigation measures to be considered, it is important to classify them appropriately as per established international practices.

3.1 Classification Schemes

Landslides come in a great variety of shapes and sizes[107]. Some are very large and cause great devastation while others are very small and cause little or no damage at all. They can be single events of slope instability, or they can be complex in nature with multiple events at one site. They can occur in a wide range of earth materials and be due to a variety of failure mechanisms. They can be classified in number of ways, each having some usefulness in emphasizing features pertinent to recognition, avoidance, control, correction or other purpose of classification. There are several attributes that have been used as different discriminating factors and criteria for identification and classification (**Table 3.1**) of landslides. Mostly, the chief criteria used in landslide classification are type of material and the type of movement **(Table 3.2)**[30, 49, 54, 72, 107, 108, 110, 136 and 154]. The type of movement describes the actual internal mechanics of how the landslide mass is displaced. The five kinematically distinct types of movement are described in the sequence fall, topple, slide, spread and flow. Hence the combination of the type of movement and material involve gives a basic description of the landslide e.g. rock fall, debris flow etc (**Table 3.3**). Since the type of landslide will determine the potential speed of movement, likely volume of displacement, distance of run-out, as well as the possible effects of the landslide and the appropriate mitigate measures to be considered, it is important to classify them appropriately. Further description of a landslide incorporates terms on the state and style of activity (**Table 3.4**).

Table 3.1 Different Discriminating Factors

Discriminating Factors	Description
Type of movement	The main movements are falls, slides and flows, but usually topples, lateral spreading and complex movements are also added to these.
Type of material	Rock, earth and debris are the terms generally used to distinguish the materials involved in the landslide process. (If the weight of the particles with a diameter greater than 2 mm is less than 20%, the material will be defined as earth; in the opposite case, it is debris.)
Activity	The concept of activity is defined with reference to the spatial and temporal conditions i.e. the state, describes the information regarding the time in which the movement took place; the distribution, the second term describes, in a general way, where the landslide is moving and style, the third term indicates how it is moving.
Movement velocity	This factor has a great importance in the hazard evaluation. A velocity range is connected to the different type of landslides, on the basis of observation of case history or site observations.
The age of the movement	The evaluation of age of landslide gives its frequency and the specific condition under which it could have occurred. It should be noted that, it is possible that phenomena could be occurred in past geological times, under specific environmental conditions which no longer act as agents today.
Geological conditions:	These represent a fundamental factor of the morphological evolution of a slope. Bedding attitude and the presence of discontinuities or faults/thrust control the slope morphogenesis.
Morphological characteristics	As the morphology is the manifestation of past and ongoing geological changes on the terrain; morphological characteristics are extremely important in the reconstruction of the technical model.
Geographical location	Landslides on their spatial context are referred so that not only geography is known but the correlation with landslide morphology and geology is also made.
Topographical criteria	With these criteria, landslides can be identified with a system similar to that of the denomination of formations. Consequently, it is possible to describe a landslide using the name of a site. In particular, the name will be that of the locality where the landslide happened with a specific characteristic type.
Type of climate	Given the changing climatic condition this criteria give particular importance to climate in the genesis of phenomena for which similar geological conditions can, in different climatic conditions, lead to totally different morphological evolution. As a consequence, in the description of a landslide, it can be interesting to understand in what type of climate the event occurred.
Causes of movements	In the evaluation of landslide susceptibility, causes of the triggers are an important step. The causes may be as “internal” and “external” referring to modifications in the conditions of the stability of the bodies. Whilst the internal causes induce modifications in the material itself which decrease its resistance to shear stress, the external causes generally induce an increase of shear stress, so that block or bodies are no longer stable. The triggering causes induce the movement of the mass. Predisposition to movement due to control factors is determining in landslide evolution. Structural and geological factors, as already described, can determine the development of the movement, inducing the presence of mass in kinematic freedom.

One type of slope failure may grade into another, slide often turn into flows. Complex slope movements are those in which there is a combination of two or more principle types of movement. There are also cases of multiple movements in which repeated failure of the same type occur in succession and compound movement are those in the failure surface is formed of a combination of curved and planar sections.

Table 3.2 A Widely used Landslide Classification Based on Varnes (1978)

Types of Movements		**Types of Materials**		
			Engineering Slope	
			Predominantly Coarse	**Predominantly Fine**
Fall		Rock fall	Debris fall	Earth fall
Topples		Rock topple	Debris topple	Earth topple
Spread		Rock spread	Debris spread	Earth spread
Flow		Rock flow	Debris flow	Earth flow
Slides	Rotational slide	Rock slump	Debris slump	Earth slump
	Translation slide/wedge	Rock block slide	Debris block slide	Earth block slide
		Rock slide	Debris slide	Earth slide
Complex		Combination of two or more principal types of movement		

3.1.1 *Classification based on rate of movement [49, 136]*

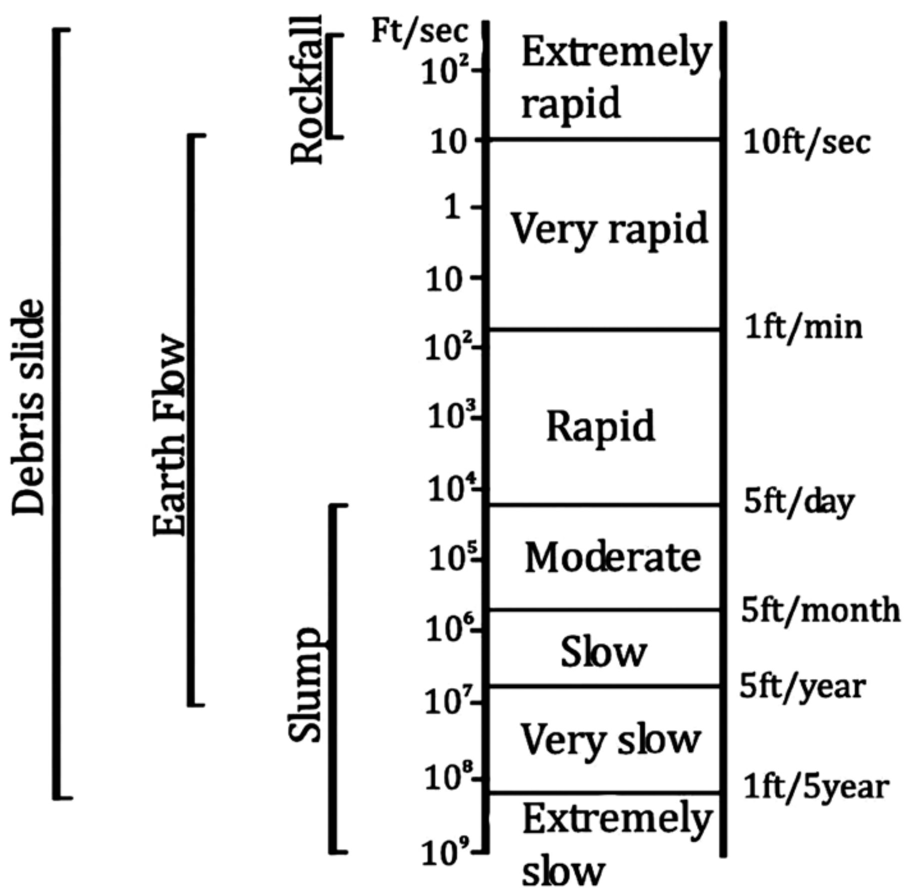


Fig. 3.1 Landslide Rate of Movement (Velocity) Classification

3.1.2 *Landslide Activity*

Table 3.4 Classification of Slopes Based on Activities[22]

<table>
<tr><th>Classification of Slope</th><th colspan="3">Description</th></tr>
<tr><td rowspan="3">I-Unstable Slopes</td><td colspan="2">Active</td><td>Material is currently moving, and landslide features are fresh and well defined</td></tr>
<tr><td colspan="2">Reactivated</td><td>Material is currently moving and represents renewed landslide activity; some landslide features are fresh and well defined; others may appear older</td></tr>
<tr><td colspan="2">Suspended</td><td>Slopes with evidence of landslide activity within the past year but is not active at present; landslide features are fresh and well define</td></tr>
<tr><td rowspan="4">II-Slope With Inactive Landslides</td><td rowspan="4">A dormant landslide is an inactive landslide which can be reactivated by its original causes or other causes. In the example shown the displaced mass begins to regain its tree cover and scarps are modified by weathering.</td><td>Dormant-historic</td><td>Slopes with evidence of previous landslide activity that have undergone most recent movement within the preceding 100 years (approximately historic time)</td></tr>
<tr><td>Dormant- young</td><td>Slopes with evidence of previous landslide activity that have undergone most recent movement during an estimated period of 100 to 5, 000 years before present (late Holocene)</td></tr>
<tr><td>Dormant-mature</td><td>Slopes with evidence of previous landslide activity that have undergone most recent movement during an estimated period of 5, 000 to 10,000 years before present (Early Holocene)</td></tr>
<tr><td>Dormant-old</td><td>Slopes with evidence of previous landslide activity that have undergone most recent movement more than 10,000 year before present (Late Pleistocene)</td></tr>
<tr><td>III-Potentially Unstable Slopes</td><td colspan="3">Slopes that show no evidence of previous landslide activity but that are considered likely to develop landslides in the future; landslide potential is indicated by analysis or comparison with other slopes.</td></tr>
<tr><td rowspan="4">IV- Apparently Stable Slopes</td><td colspan="2">Stabilized</td><td>Slopes with evidence of previous landslide activity but that have been protected from its original causes by remedial measures.</td></tr>
<tr><td colspan="2">Abandoned</td><td>An abandoned landslide is an inactive landslide which is no longer affected by its original causes.</td></tr>
<tr><td colspan="2">Relict</td><td>A relict landslide is an inactive landslide which developed under climatic or geomorphological conditions not currently present.</td></tr>
<tr><td colspan="2">Stable</td><td>Slopes that show no evidence or previous landslide activity and that by analysis or comparison with other slopes are considered stable</td></tr>
</table>

Table 3.5 shows the distribution of activity depending on the direction of the surface of rupture (slide)[165].

Table 3.5 Distribution of Activities

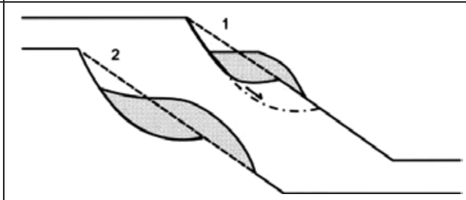
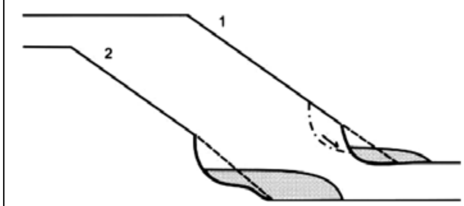
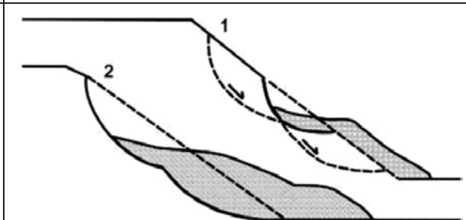
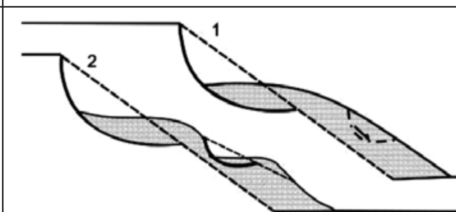
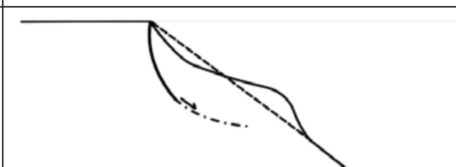
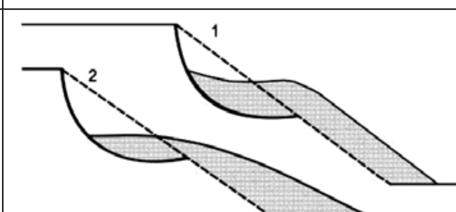
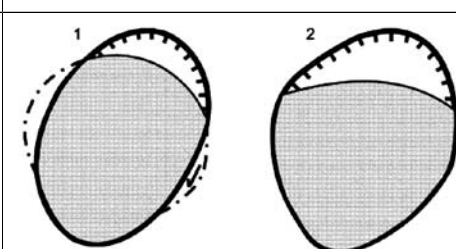
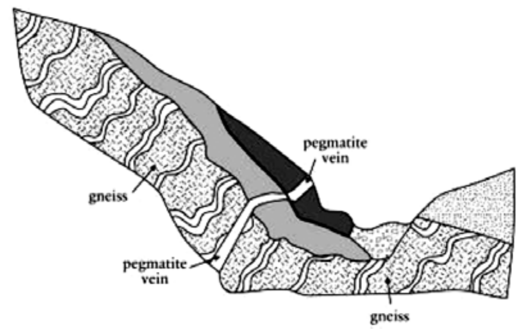
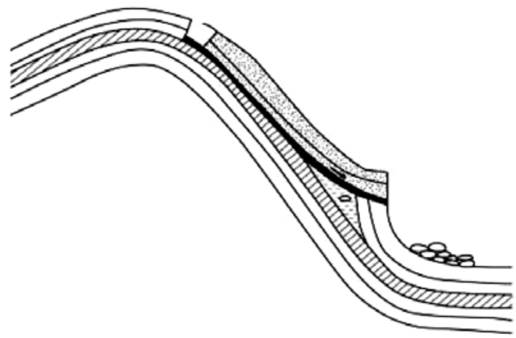
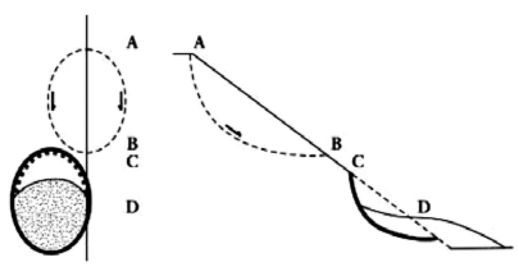
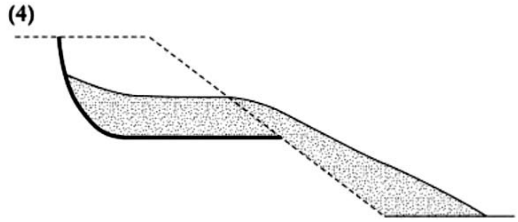
Distribution	Description	Figure
Advancing	In an advancing landslide the rupture surface is extending in the direction of movement.	
Retrogressive	In a retrogressive landslide the rupture surface is extending in the direction opposite to the movement of the displaced material.	
Enlarging	In an enlarging landslide the rupture surface of the landslide is extending in two or more directions.	
Diminishing	In a diminishing landslide the volume of displaced material is decreasing.	
Confined	In a confined landslide there is a scarp but no rupture surface visible at the foot of the displaced mass.	
Moving	In a moving landslide the displaced material continues to move without any visible change in the rupture surface and the volume of the displaced material.	
Widening	In a widening landslide the rupture surface is extending into one or both flanks of the landslide.	

Table 3.6 Shows the style of the activities indicating the way in which different movements contribute to the landslides[165].

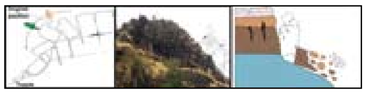
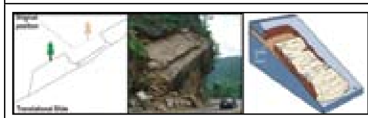
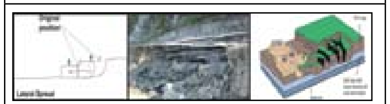
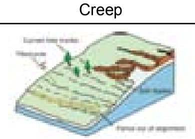
Table 3.6 Style of Activities

Style	Description	Figure
Complex	A complex landslide exhibits at least two types of movement (falling, toppling, sliding, spreading and flowing) in sequence. In the example shown a gneiss and a pegmatite vein toppled with valley incision. Alluvial deposits fill the valley bottom. After weathering had weakened the toppled material some of the displaced mass slid further down slope.	
Composite	A composite landslide exhibits at least two types of movement simultaneously in different parts of the displacing mass. In the example shown the limestones have slid on the underlying shales causing toppling below the toe of the slide rupture surface.	
Successive	A successive landslide is the same type as a nearby, earlier landslide, but does not share displaced material or rupture surface with it. In the example shown the later slide AB is the same type as CD but does not share displaced material or a rupture surface with it.	
Single	A single landslide is a single movement of displaced material.	

3.2 Description of Type of Movements

Table 3.7 Gives Description of Different Types of Movements [54, 107, 110 and 145].

Table 3.7 Description of Type of Movements

Type of movement	Descriptions	Triggering Mechanism
Fall 	The detachment of slope material i.e. soil or rock, or both, from a steep slope along a surface on which little or no shear displacement has occurred is termed as fall. The material descends mainly by falling, bouncing, or rolling. The volume of material in a fall can vary substantially, from individual rocks or clumps of soil to massive blocks thousands of cubic meters in size. The velocity of movement is very rapid to extremely rapid. Except the rolling velocity of displaced mass which depends on slope steepness. The fall is prefixed with some nouns like rock, debris and soil depending upon the type of material. Rockfall is a fall of newly detached mass from an area of bed rock. Debris fall is a fall of debris which is composed of detrital fragments prior to failure.	Undercutting of slope by natural processes such as streams and rivers or differential weathering (such as the freeze/thaw cycle), human activities such as excavation during road building and (or) maintenance, and earthquake shaking or other intense vibration. Effects (direct/indirect) Falling material can be life-threatening. Falls can damage property beneath the fall-line of large rocks. Boulders can bounce or roll great distances and damage structures or kill people. Damage to roads and railroads is particularly high: rockfalls can cause deaths in vehicles hit by rocks and can block highways and railroads.
Topple 	Topples 54 can consist of rock, debris (coarse material), or earth materials (fine grained material). The material involved usually leans forward in bulk but when it fails, at the base, it rapidly rotates onto the slope below and breaks up, bounces, roles or slides forward. Topples range from extremely slow to extremely rapid, sometimes accelerating throughout the movement. This kind of movement can be extremely destructive, especially when failure is sudden and (or) the velocity is rapid.	Sometimes driven by gravity exerted by material located upslope from the displaced mass and sometimes by water or ice occurring in cracks within the mass; also, vibration, undercutting, differential weathering, excavation, or stream erosion.
Rotational Landslide 	A landslide on which the surface of rupture is curved upward (spoon-shaped) and the slide movement is more or less rotational about an axis that is parallel to the contour of the slope. The displaced mass may, under certain circumstances, move as a relatively coherent mass along the rupture surface with little internal deformation. The head of the displaced material may move almost vertically downward, and the upper surface of the displaced material may tilt backwards toward the scarp. If the slide is rotational and has several parallel curved planes of movement, it is called a slump. As rotational slides occur most frequently in homogeneous materials, they are the most common landslide occurring in "fill" materials.	Intense and (or) sustained rainfall or rapid snowmelt can lead to the saturation of slopes and increased groundwater levels within the mass; rapid drops in river level following floods, ground-water levels rising as a result of filling reservoirs, or the rise in level of streams, lakes, and rivers, which cause erosion at the base of slopes. These types of slides can also be earthquake-induced.
Translational Landslide 	The mass in a translational landslide moves out or down and outward along a relatively planar surface with little rotational movement or backward tilting. This type of slide may progress over considerable distances if the surface of rupture is sufficiently inclined, in contrast to rotational slides, which tend to restore the slide equilibrium. The material in the slide may range from loose, unconsolidated soils to extensive slabs of rock, or both. Translational slides commonly fail along geologic discontinuities such as faults, joints, bedding surfaces, or the contact between rock and soil.	Primarily intense rainfall, rise in ground water within the slide due to rainfall, snowmelt, flooding, or other inundation of water resulting from irrigation, or leakage from pipes or human-related disturbances such as undercutting. These types of landslides can be earthquake-induced.
Lateral Spreads 	Lateral spreads usually occur on very gentle slopes or essentially flat terrain, especially where a stronger upper layer of rock or soil undergoes extension and moves above an underlying softer, weaker layer. Such failures commonly are accompanied by some general subsidence into the weaker underlying unit. Velocity of movement may be slow to moderate and sometimes rapid after certain triggering mechanisms, such as an earthquake.	Triggers that destabilize the weak layer include: □ Liquefaction of lower weak layer by earthquake shaking, □ Natural or anthropogenic overloading of the ground above an unstable slope, □ Saturation of underlying weaker layer due to precipitation, snowmelt, and (or) ground-water changes, □ Liquefaction of underlying sensitive marine clay following an erosional disturbance at base of a riverbank/slope, □Plastic deformation of unstable material at depth (for example, salt).
Debris Flows 	A form of rapid mass movement in which loose soil, rock and sometimes organic matter combine with water to form a slurry that flows downslope. Debris flows can be deadly as they can be extremely rapid and may occur without any warning.	Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt that erodes and mobilizes loose soil or rock on steep slopes. Debris flows also commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt- and sand-sized material.
Debris Avalanche 	Debris avalanches are essentially large, extremely rapid; often open-slope flows formed when an unstable slope collapses and the resulting fragmented debris is rapidly transported away from the slope. In some cases, snow and ice will contribute to the movement if sufficient water is present, and the flow may become a debris flow and (or) a lahar.	In general, the two types of debris avalanches are those that are "cold" and those that are "hot." A cold debris avalanche usually results from a slope becoming unstable, such as during collapse of weathered slopes in steep terrain or through the disintegration of bedrock during a slide-type landslide as it moves downslope at high velocity. At that point, the mass can then transform into a debris avalanche. A hot debris avalanche is one that results from volcanic activity including volcanic earthquakes or the injection of magma, which causes slope instability.
Earth flow	Earth flows can occur on gentle to moderate slopes, generally in fine-grained soil, commonly clay or silt, but also in very weathered, clay-bearing bedrock. The mass in an earth flow moves as a plastic or viscous flow with strong internal deformation. Susceptible marine clay (quick clay) when disturbed is very vulnerable and may lose all shear strength with a change in its natural moisture content and suddenly liquefy, potentially destroying large areas and flowing for several kilometers. Size commonly increases through head scarp retrogression. Slides or lateral spreads may also evolve downslope into earth flows. Earth flows can range from very slow (creep) to rapid and catastrophic.	Triggers include saturation of soil due to prolonged or intense rainfall or snowmelt, sudden lowering of adjacent water surfaces causing rapid drawdown of the ground-water table, stream erosion at the bottom of a slope, excavation and construction activities, excessive loading on a slope, earthquakes, or human-induced vibration.
Creep 	Creep is the imperceptibly slow, steady, downward movement of slope-forming soil. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. There are generally three types of creeps: (1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature; (2) continuous, where shear stress continuously exceeds the strength of the material; and (3) progressive, where slopes are reaching the point of failure.	For seasonal creep, rainfall and snowmelt are typical triggers, whereas for other types of creep there could be numerous causes, such as chemical or physical weathering, leaking pipes, poor drainage, destabilizing types of construction, and so on.

4 LANDSLIDE HAZARD MAPPING, VULNERABILITY AND RISK ASSESSMENT

Landslide susceptibility, hazard and risk mapping of any hilly terrain, prior to development, are the basic need not only for minimizing the risk to life and property and safety of the public and infrastructure from landslides and like phenomena but also for the quality and durability of the infrastructure in disaster prone areas.

The landslide hazard, vulnerability and risk assessment is based upon the use of three major steps: susceptibility mapping, hazard mapping and risk mapping (**Fig. 4.1**). In susceptibility mapping, the locations of areas liable to undergo landslide are identified. In hazard mapping, the probability of failure is estimated using a number of techniques. In risk mapping, the landslide hazard assessment is combined with an estimate of the vulnerability of the total infrastructure and population to produce an estimate of landslide risk.

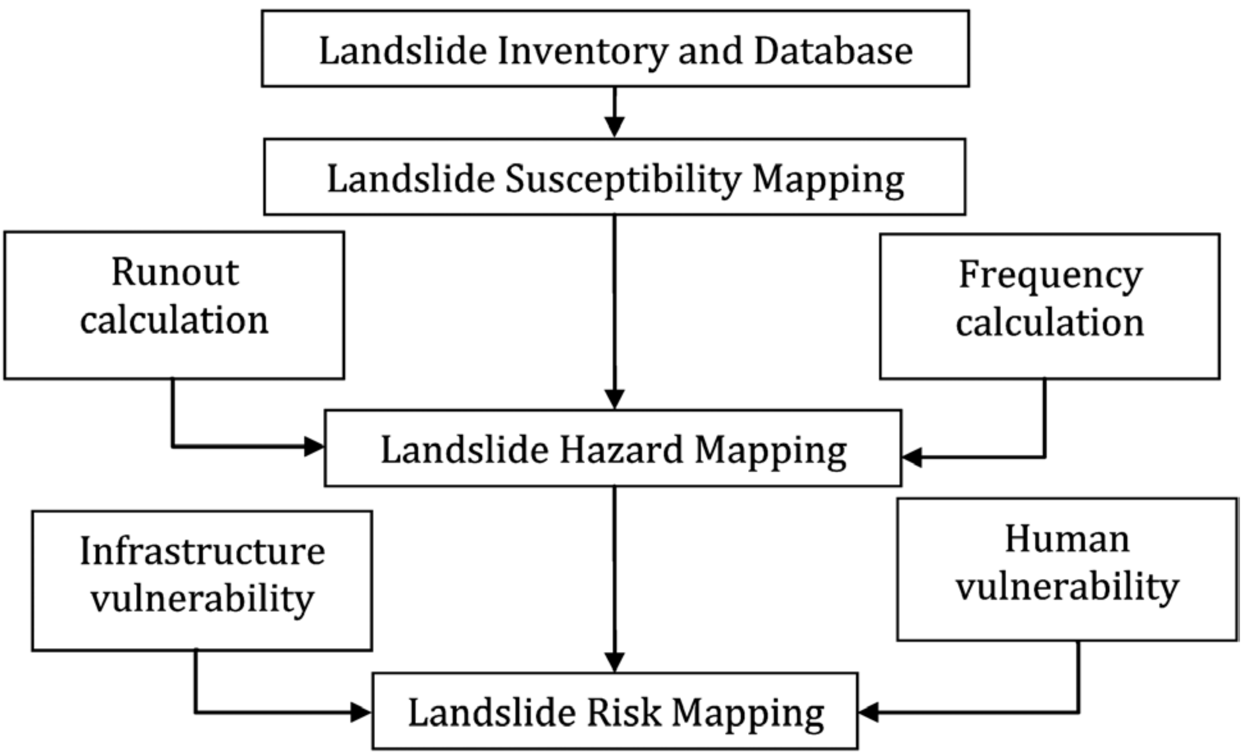


Fig. 4.1 Basic Framework of Hazard, Vulnerability and Risk

4.1 Recommended Landslide Mapping Scale and their Application

Landslide zoning maps should be prepared at a scale appropriate for displaying the information needed at a particular zoning level understandable to the working engineers and the policy makers. The scale of mapping is generally controlled by the aim of the project for which the maps are being planned. **Table 4.1** below summarizes map scales and the landslide inventory, susceptibility, hazard and risk mapping to which they are usually applied[51].

Table 4.1 Landslide Zoning Mapping Scale and their Application

Scale Description	Indicative Range of Scales	Examples of Zoning Application
Regional planning (Policy level)	1:50,000 - 1:1,00,000	Landslide inventory and susceptibility to inform policy makers/planners and the general public.
Specific policy decision (regional level)	1:25,000 - 1:50,000	Landslide inventory and susceptibility zoning for regional and local development/ very large scale engineering projects. Preliminary level hazard mapping for local areas.
Project based planning (Advance level planning)	1:5,000 - 1:25,000	Landslide inventory and susceptibility and hazard zoning for local areas. Preliminary level risk zoning for local areas. Advance stage of planning for large engineering structure roads and railways.
Specific site planning	1:500 - 1:5,000	Intermediate and advance level hazard and risk zoning for local and site specific areas and for the design phase of large engineering structure, roads and railways.

4.2 Landslide Hazard Analysis Techniques and Maps

Existing landslides and their relationship with the key factors such as slope steepness, lithology variation, groundwater conditions etc. gives an understanding of the conditions and processes controlling landsliding and forms the basis for assessing landslide susceptibility and ultimately hazard[50]. **Table 4.3** provides a summary of hazard analysis techniques and mapping.

Table 4.3 Hazard Analysis Techniques in Relation to Mapping Scales

Type of Analysis	Technique	Characteristics	Scale of Use Recommended		
			Regional	Medium	Large
			1:50,000 – 1:1,00,000	1:25,000 – 1:50,000	1:500 – 1:5,000
Inventory	Landslides distribution analysis	Analyze distribution and classification of landslides	Yes	Yes	Yes
	Landslide activity analysis	Analyze temporal changes in landslide pattern	No	Yes	Yes
	Landslide activity analysis	Calculate landslide density in terrain units or as isopleth map	Yes	Yes	No
Heuristic	Geomorphologic analysis	Use in-field expert opinion in zonation	Yes	Yes	Yes
	Qualitative map combination	Use expert-based weight values of parameter maps	Yes	Yes	No
Statistical	Bi-variate statistical analysis	Calculate importance of contributing factor combination	No	Yes	No
	Multivariate statistical analysis	Calculate prediction formula from data matrix	No	Yes	No
	Probabilistic (Magnitude/ Frequency)	Calculate prediction from inventory and time period using power law	Yes	Yes	No
Deterministic	Safety factor analysis	Apply hydrological and slope stability models	No	No	Yes

Heuristic or qualitative methods use expert interpretation of geological and historical information on landslides to estimate the susceptibility of areas to landslide events. A combination of qualitative and quantitative information form the basis of relative hazard that can be classified into landslide susceptibility classes (e.g. high, medium, low).

Statistical hazard analysis methods use landslides, geological, topographic and vegetation etc information to calculate the susceptibility to landslide or the probability of landslide events. By definition, determining landslide hazard requires determining the magnitude and frequency of landslide events. However, both the parameters are difficult to be determined, particularly when the data are scar.

Determining the spatial and temporal extent of landslide hazard involves identifying areas which are, or could be, affected by a landslide and assessing the probability of similar landsliding occurring within a specified time period. Specifying a time frame for the future occurrence of a landslide is difficult and often not possible.

The prediction and forecasting of landslides relies on the knowledge gained from the production of hazard maps. The stability and the possible vulnerabilities of slopes are researched to determine how safe the area around the slope is from possible landslides.

4.3 Landslide Database Inventory

The landslide database and inventory is an important and, in fact, a first step towards not only the landslide hazard mapping and risk assessment but also towards any of the landslide hazard mitigation and management programs. The inventory of landslides before zonation is prerequisite because an area can be said susceptible for landslides, when the terrain conditions are comparable to those where a slide has occurred[45]. Landslide inventory maps show the distribution of past and active landslides[4], their relative activity, landslide density and/or geomorphic attributes, within an area. Some geomorphic attributes include slope, slope aspect, bedrock lithology and structure, soil type, depth of overburden, moisture content and geomorphic processes such as gullying and soil erosion etc. Each landslide is typically mapped as a geographically referenced polygon; small landslides can be represented by a geographically referenced point. If possible, each landslide should be assigned a landslide type and, where possible, other information should be included such as date of occurrence, state of activity and approximate volume.

For small landslides in natural slopes, the quality of the inventory will be enhanced by carrying out surface as well as aerial photograph-based interpretation. Basic small or medium scale landslide inventory mapping at regional or local level may be followed by intermediate or advanced mapping of higher susceptibility areas (**Table 4.4**). The inventory should be mapped at a larger scale than the susceptibility, hazard or risk zoning maps. Different information can be mapped depending on the scale[33].

Table 4.4 Activities Required while Preparing a Landslide Inventory, Susceptibility, Hazard and Risk Mapping

Characterisation Method	Activities			
	Landslide Inventory	Landslide Susceptibility Mapping	Landslide Hazard Mapping	Landslide Risk Mapping
Basic (1:50,000 to 1:100,000)	Prepare an inventory of landslides in the area from aerial photographs and /or satellite imagery, and by mapping and from historic records. The inventory includes the location, classification, volume (or area) and so far as practicable the date of occurrence of landsliding.	Prepare a geomorphologic map and landslide inventory.	Same as landslide susceptibility mapping + assessment of frequency, velocity, run-out of landslide	Same as landslide hazard mapping + element at risk, consequences of hazard
	Identify the relationship to topography, geology and geomorphology.	Prepare calculations of the % of the total landslide count for each susceptibility class, the % of the area affected by landslides for each class and the % of each class in comparison to the total study area.		
	Show this information on inventory maps along with topographic information including contours, property boundaries, mapping grid, roads and other important features such as streams and water-courses.	Correlate the incidence of landsliding different factors to delineate areas susceptible to landsliding.		
		For regional zoning correlate the incidence of landsliding with annual rainfall or snowmelt, and/or seismic loading.		
		Prepare the landslide susceptibility zoning map superimposed on the topography with a suitable legend. Implement the data and the maps in a GIS.		
Intermediate (1:10,000 to 1:25,000)	The same activities as Basic plus	The same activities as basic plus		
	Identify landside features/initial surface	Obtain basic soil classifications and depths in the study area.		
	Influence of manmade activities on incidences of landslide.	Classify more complex terrain units. Qualitative rating of the landslide susceptible areas based on overlapping techniques.		
		Develop quantitative ratings (often relative rating) of landslide susceptible areas based on data treatment techniques.		
	Analysis of land use vs. human activities	Implement the data and the maps in a GIS		
Advanced (>1:5,000)	The same activities as Intermediate plus	The same activities as Intermediate plus		
	Detailed Investigations	Detailed mapping and geotechnical investigations to develop an understanding of the mechanics of landsliding, hydrogeology and stability analyses.		
	Advanced temporal cataloguing of periodic reactivations of the same hazard and temporal windowing of specific triggering events to provide periodic inventory data sets which can then be used in advanced validation approaches.	Perform data treatment analysis (discriminate; neural networks; fuzzy logic; logistic regression; etc) and develop quantitative ratings to obtain susceptibility classes.		
		Perform stability analysis.		
		Implement the data and the maps in a GIS (recommended).		

Landslide Information Form[163]

Landslide ID		Survey No		Name of Surveyor		
GENERAL INFORMATION						
Name of Slide		Type of Slide				
Location :		Toposheet No				
On /Off Highway		Coordinates	Lat	Long		
Village / Town		Causative Factor				
Tehsil / Taluka		Site Description				
District		Activity	Active		Dormant	
State						
Date of Occurrence	Year:	Month:	Day:	Time:		
Casualties	Human		Livestock		Infrastructure	
Probability of future risk	Degree of Risk:	Organized Remedial measures				
Economic losses:						
Direct		Indirect		Socio-economic Activity		

4.4 Landslide Susceptibility Mapping

Landslide susceptibility mapping usually involves developing an inventory of landslides which have occurred in the past together with an assessment of the areas with a potential to experience landsliding in the future, but with no assessment of the frequency (annual probability) of the occurrence of landslides[51]. Susceptibility mapping involves the rating of the terrain units according to their propensity to produce landslides. This is dependent on the topography, geology, geotechnical properties, climate, vegetation and anthropogenic factors such as development and clearing of vegetation. The scale of susceptibility is usually a relative one.

It should be recognized that the study area may be susceptible to more than one type of landslide e.g. rock fall and debris flows, and may have a different degree of susceptibility (and in turn hazard) for each of these[33]. In these cases it will often be best to prepare separate susceptibility maps for each type of landslide and to combine them to obtain the global landslide hazard map of the area.

Procedure for landslide susceptibility mapping:

- Defining the Aim for which the landslide susceptibility or hazard information is needed
- Based on the aim for which the map is needed, scale of mapping etc. are to be selected
  - ➢ Find out whether topographic & other information are available on that scale, if yes - move further, if not - decide whether such base maps are to be created
  - ➢ If base map to the desired scale are not available we look for Aerial Photographs/imageries of an appropriate resolution which will be helpful in developing the base map.

- Development of existing landslide map which helps in identifying the factors and to prioritize them (Inventory is first step).
- Identification of the factors and their prioritization based on their contribution in inducing the slope stability.
- Creation of analytical maps for each of the selected factors.
- Characterization of each factor, as per their physical, chemical, engineering characteristics.
- Grade/rate each of the factors, as per their characteristics, and their possible as well as established role in inducing landslide hazard process.
- Creation of a combined map, by superimposing one factor maps on another and so on as per priority given to each factor in GIS platform.
- Total hazard evaluation, the sum total of all the accorded grading/rating.
- Final geo-engineering mapping or susceptibility map.
- Probability analysis, which also serves the purpose of checking the final geo-engineering map.

4.5 Landslide Hazard Zonation (LHZ) Mapping

Susceptibility maps are prepared to locate/identify the areas susceptible to future stability problems and the landslide hazard mapping is a step further of susceptibility. Such analysis is an iterative process, whereby initially a broad appreciation of the hazard, events, and then likelihood (probability) of occurrence, and the resulting consequences are developed. This will assist in determining which aspects need more in depth investigation. The technique used in the Hazard mapping take into consideration the knowledge of past events, present condition prevailing in the area and anticipation of future behavior of slope stability. The hazard may be expressed as the frequency of a particular type of landslide of a certain volume or landslides of a particular type, volume and velocity (which may vary with distance from the landslide source)[52]. **Fig. 4.2** shows the methodologies used to prepare landslide hazard mapping[64].

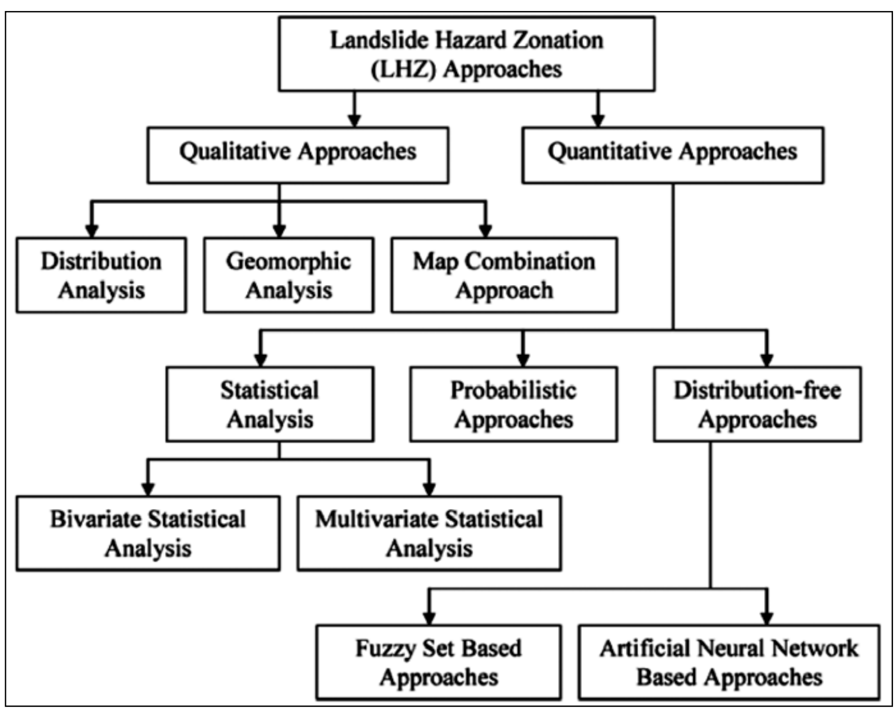


Fig. 4.2 Flowchart of Landslide Hazard Zonation

The preparation of landslide hazard map required all the steps of susceptibility mapping in preceding section with addition of assessment of landslide frequency, velocity and run out distance.

* In India, Bureau of Indian Standards (BIS) has formulated guidelines for preparation of landslide hazard zonation maps in the year 1998 (BIS -code; IS 14496 (Part 2).
* "Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning" Ref: AGS (2007a) also devised preparation of landslide hazard map.

4.5.1 *Recommended Landslide Hazard Zoning Descriptors*

The manner in which landslide hazard is described depends on the type of landslide[51]. For small slides and rock falls the hazard is described in terms of the number of slides per length of source area/annum, or the number of landslides per square kilometer of source area/ annum. For large landslides hazard is described in terms of the annual probability of active sliding, or for active slides the annual probability movement will exceed a defined distance or the annual probability that cracking within a slide exceeds a defined length.

Table 4.5 presents recommended descriptors (as given in Australian guidelines) for the most common landslide and rock fall situations.

Table 4.5 Recommended Descriptors for Hazard Zoning

Hazard Descriptor	Rock Falls/Slides from Cut and Fill Slopes on Roads or Railways and Small Landslides on Natural Slopes
	Number/annum/km
Very High	>10
High	1 to 10
Moderate	0.1 to 1
Low	0.01 to 0.1
Very Low	< 0.01

4.5.2 *Frequency Assessment*

The frequency of landslide may be expressed in terms of the number of landslides of certain characteristics that may occur (probability) in the study area in a given span of time (generally per year, but the period of reference might be different if required).

For better understanding and useful references of landslide frequency assessment refer to Australian Geomechanics "Commentary on Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning" AGS (2007b).

4.5.3 *Intensity Assessment*

Intensity is the measure of the damaging capability of the landslide. In slow moving landslides persons are not usually endangered while damages to buildings and infrastructures might be high although, in some cases, only evidenced after long periods of time. By contrast rapid movements of small and large masses may have catastrophic consequences for both persons and structures. For this reason it is desirable to describe the intensity of the landslides in the zoning study.

The same landslide may result in different intensity values along the path (for instance, the kinetic energy of a rock fall changes continuously along its trajectory)[33].

4.5.4 *Landslide Characterization, Travel Distance and Velocity*

For landslide characterization, travel distance and velocity, refer to Australian Geomechanics "Commentary on Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning" AGS (2007b). It provides more detail on the activities required to characterize the landslides for the four main classes of landslides and suggested useful references. In most of the cases where intermediate methods are being used basic methods will also be used. For advanced methods, intermediate and basic methods will also be used. Note that much of these activities will be carried out in GIS and the terms used here are generic. It should be noted that the more advanced the characterization method the larger scale of the mapping and level of detail of information and understanding of slope processes is required.

4.6 Landslide Risk Management

Figure 4.4 illustrates fundamental framework for landslide risk management[114].

4.6.1 *Landslide Risk Mapping*

It takes the outcomes of hazard mapping and assesses the potential damage to persons (annual probability the person most at risk loses his or her life) and to property (annual value of property loss) for the elements at risk, accounting for temporal and spatial probability and vulnerability[51]. In current case it includes risk of life to commuters, travelling vehicles and highways.

4.6.2 *Principles for Planning Approaches*

1. Gather accurate landslide hazard information.

   Identifying landslide-prone areas and plotting them on planning maps is essential for communicating the risk they may present and mitigating such hazards[50].

2. Plan to avoid landslide hazards before development and subdivision.

   Landslide hazards can be avoided by preventing development on known landslide hazard areas. Where avoidance is not possible, mitigation measures can be applied to reduce the risk can reduce risk through appropriate engineering works.

3. Take a risk-based approach in areas already developed or subdivided.

   Planning for land use in landslide-prone areas helps to avoid or mitigate the increased risks from landslide hazards caused by land-use intensification (such as urban in fill) and inappropriate building.

4. Communicate risk of landslides in built-up areas.

   One of the most difficult problems concerning landslide hazards is dealing with existing urban areas where buildings/highways are constructed on or close to a landslide. The ideal approach in this situation is to avoid further development in high-risk landslide prone areas, limit existing-use rights to rebuild, and limit the use of buildings/highways.

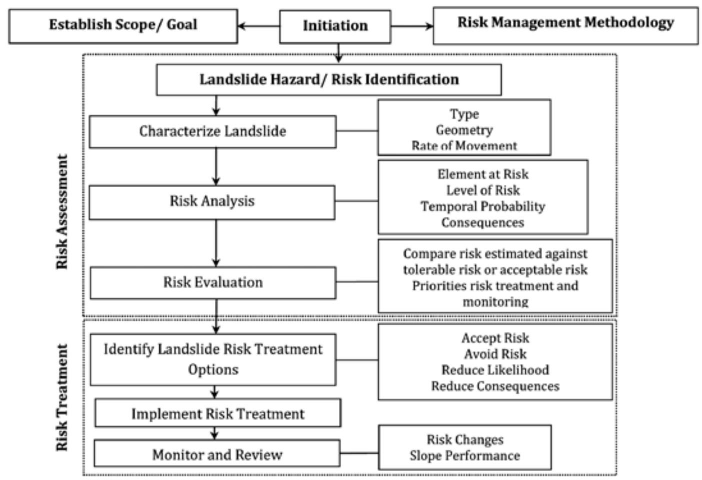


Fig. 4.4 Framework for Landslide Risk Management

4.6.3 *Recommended Landslide Risk Zoning Descriptors*

Table 4.7 & 4.8 presents the recommended descriptors for landslide risk zoning using life loss and property criteria. These are based on annual individual risk for the person most at risk. If there is a potential for a large number of persons to be killed in one landslide event there should be an assessment of societal risk.

Table 4.7 Recommended Descriptors for Risk Zoning using Life Loss Criteria

Annual Probability of Death of the Person Most at Risk in the Zone	Risk Zoning Descriptors
$>10^{-3}$ /annum	Very High
10^{-4} to 10^{-3} /annum	High
10^{-5} to 10^{-4} / annum	Moderate
to 10^{-5} /annum	Low
$<10^{-6}$ /annum	Very Low

Table 4.8 Recommended Descriptors for Risk Zoning using Property Loss Criteria

Likelihood		Consequences to Property (With Indicative Approximate (Cost of Damage)[1]				
	Isndicative Value of Approximate Annual Probability	**1:Catastrophic 200%**	**2:Major 60%**	**3:Medium 20%**	**4:Minor 5%**	**5:Insignificant 0.5%**
A ALMOST CERTAIN	10^{1}	VH	VH	VH	H	M or L [2]
B LIKELY	10^{2}	VH	VH	H	M	L
C POSSIBLE	10^{3}	VH	H	M	M	VL
D UNLIKELY	10^{4}	H	M	L	L	VL
E RARE	10^{5}	M	L	L	VL	VL
F BARELY CREDIBLE	10^{6}	L	VL	VL	VL	VL

Notes: (1) As a percentage of the value of the property.

(2) For Cell A5, may be subdivided such that a consequence of less than 0.1% is Low Risk.

(3) L low, M medium, H high, VL very low, VH very high

4.6.4 *Risk Analysis*

Risk analysis involves acquiring information on landslide hazards, as well as considering the consequences if people and property are affected by landslides[50]. Firstly, a thorough assessment of the types, characteristics and frequency of landslides in the area of interest is carried out as part of the hazard identification. Secondly, a consequence analysis establishes the elements at risk (people/property/assets).

4.6.5 *The Elements of Hazard and Vulnerability*

These two elements - hazard and vulnerability - are essential in risk assessment: hazard, as the probability of occurrence of a harmful natural event, and vulnerability as susceptibility to injury or damage if the event occurs, and the ability to protect you against it. This leads to risk as the product of the two, expressing the probability of occurrence and the magnitude of the possible damage – in other words, the probable loss or injury.

Risk = hazard x vulnerability

However, it is important to remember that a large part of the vulnerability can be reduced through human capability for prevention or self-protection ("coping strategies")[53].The absence of coping strategies is part of vulnerability, and has to be taken into account in the vulnerability analysis.

4.6.6 *Elements at Risk*

Different levels of hazard can be acceptable to various elements at risk depending on the consequences of a landslide occurring at a particular site[50]. The elements at risk are the population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by the landslide hazard[33]. These need to be assessed for existing and proposed development.

4.6.7 *Voluntary and Involuntary Risk*

Individual and organizations are willing to accept greater voluntary risks, that is, risks that are perceived to be within their control. Residential occupants, rarely consider landslide risks as voluntary. Such landslide risks are typically considered involuntary and thus landslide safety criteria values are likely to be less than the values reported earlier. As normally noticed in India, workers are generally at work at even high risk landslide areas in that case risk to workers from landslides considered voluntary because employees know that benefits (income) are, at least, partial compensation for the perceived risks, provided the risk are adequately understood and communicated.

4.6.8 *Measures of Consequence*

The consequences of a landslide are commonly described in terms of the cost of damage, and the number of deaths or injuries (casualties)[50]. The consequences are often calculated using the vulnerability (V) of the elements at risk to the landslide.

The factors which most affect vulnerability of property /individual are:

- The volume of the slide in relation to the element at risk.
- The position of the element at risk, e.g. on the slide, or immediately down slope.
- The magnitude of slide displacement, and relative displacements within the slide (for elements sited on the slide).
- The rate of slide movement.
- Whether the landslide debris buries the person(s).
- Whether the person(s) are in the open or enclosed in a vehicle or building.
- Whether the vehicle or building collapses when impacted by debris.
- The type of collapse if the vehicle or building collapses.

It should be noted that the vulnerability refers to the degree of damage (or damage value in absolute or relative terms) which is judged to be likely if the landslide does occur.

4.6.9 *Risk Estimation*

Risk is the combination of the likelihood and potential consequences of (or vulnerability to) a hazard. A landslide hazard may be assessed as "extreme", but if there are no vulnerable elements then there is no risk[50]. Landslide risk analysis is an iterative process, whereby initially a broad appreciation of the hazard, events, and then likelihood (probability) of occurrence, and the resulting consequences are developed. This will assist in determining which aspects need more in depth investigation.

4.6.10 *Quantitative Risk Estimation*

Quantitative risk estimation involves integration of the frequency analysis and the consequences[138].

The risk can be calculated:

$$R = P_H * P_{S:H} * P_{T:S} * V *_E$$

where,

R = risk (annual probability of loss property value/life).

P_H = annual probability of the landslide occurring.

$P_{S:H}$ = spatial probability that the landslide will reach the property/individual, taking into account the travel distance and travel direction.

$P_{T:S}$ = temporal spatial probability that the individual will be present when landslide occurs. For houses and other buildings P (T: S) = 1.0. For Vehicles and other moving elements at risk 1.0 < P (T: S) > 0.

V = vulnerability or probability of life loss/property value loss.

E = element at risk (the value or net present value of the property and number of people at risk).

4.6.11 *Risk Assessment*

Risk assessment involves evaluating risks, making judgments on the acceptability of the risks and evaluating remedial options and mitigation measures [50]. Such assessments depend on the likelihood (probability) and consequences of the landslide hazard events being considered, and societal acceptance of certain risk levels. This is where policy and decision makers overlap with the geological and geotechnical professionals in making decisions about acceptable risk and appropriate development options.

In assessing the landslide hazard and risk, a local authority should also take account of:

- community values and expectations (what the community wants and what it does not want)
- which areas are, or are likely to be, under pressure for development
- what infrastructure already exists near a landslide hazard (buildings, network utilities etc) and the value of that infrastructure
- what level of risk the community is prepared to accept or not accept (in practice, it is easier to define what the community will not accept using community reactions to past events as a guide)
- Consideration of the feasibility (effectiveness versus cost) of possible engineering solutions or other risk reducing mitigation works.

Landslide risk assessment requires an understanding of the likely magnitude or consequences of different types of landslide events, and the risks of injury or loss of life and damage to property and investment. It also requires consideration of the cost of clean-up, or repair or replacement of damaged property or services after the event. The estimation of risk is relatively simple due to the use of a risk matrix, whereby the product of likelihood and consequence indicates the level of risk[31].

4.6.12 *Landslide Risk Treatment/Remedial Measures*

Risk Treatment is the final stage of the landslide risk management process and provides the methodology of controlling the risk. Feasible options for risk mitigation for each risk assessment are to be identified and discussed including the reduced risk by adoption of those options.

Alternative methods to be explored include[138]:

- Accept the risk, which is only an option subject to the criteria set by the regulator. Where the risk is not tolerable then risk mitigation measures are required.
- Avoid the risk, such as relocation of the site of proposed development, or revise the form of the development, or abandon the development (though this may still require some risks to be controlled due to possible effect on third parties adjacent or nearby).
- Reduce the frequency of landslide, by stabilization measures to control the initiating circumstances, such as by re-profiling the surface geometry

where existing slopes are 'over steep', by provision of improved surface water drainage measures, by provision of subsurface drainage scheme, by provision of retaining structures such as retaining walls, anchored walls or ground anchors etc.

- Reduce the consequences, by provision of defensive stabilization measures or protective measures such as a boulder catch fence, or amelioration of the behavior of the landslide, or by relocation of the development to a more favorable location.
- Manage the risk by establishing monitoring and warning systems, such as by regular site visits, or by survey, which enable the risks to be managed as an interim measure in the short term or as a permanent measure for the long term by alerting persons potentially affected to a change in the landslide condition. Such systems may be regarded as a method of reducing the consequences provided it is feasible for sufficient time to be available between the alert being raised and appropriate action being implemented.
- Transfer the risk, such as by requiring another authority to accept the risk (possibly via a court appraisal) or by provision of insurance to cover potential property damage.
- Postpone the decision, where there is sufficient uncertainty resulting from the available data, provided that additional investigations or monitoring are likely to enable a better risk assessment to be completed. Postponement is only a temporary measure and implies the risks are being temporarily accepted, even though they may not be acceptable or tolerable.

4.6.13 *Disaster Risk Management - Concept and Areas for Action*

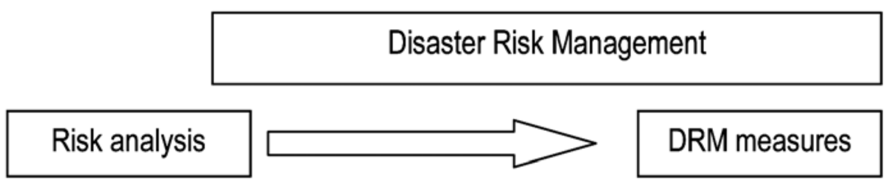
Disaster management (DM) includes measures for before (prevention, preparedness, risk transfer), during (humanitarian aid, rehabilitation of the basic infrastructure, damage assessment) and after disaster (disaster response and reconstruction)[53]. Disaster risk management (DRM) (**Fig 4.5**) is part of disaster management, focusing on the before (risk analysis, prevention, preparedness) of the extreme natural event, and relating to during and after of the disaster only through risk analysis. DRM is an instrument for reducing the risk of disaster primarily by reducing vulnerability, based on social agreements resulting from risk analysis. These social agreements are the result of a complex social process in which all social strata and interest groups participate. They are a necessary basis for resisting the future effects of extreme natural events (prevention, preparedness). The primary area of action of a DRM is reducing vulnerability and strengthening self protection capabilities.

Disaster prevention includes those activities which prevent or reduce the negative effects of extreme natural events, primarily in the medium to long term. These include political, legal, administrative, planning and infrastructural measures.

Preparedness for disasters is intended to avoid or reduce loss of life and damage to property if an extreme natural event occurs. The participating institutions and the population at hazard are prepared for the situation that might arise, and precautions are taken. In addition to increasing the alert level, mobilizing the self-help resources of the population for the emergency and operating a monitoring system, this includes the following measures:

1) Participative formulation of emergency and evacuation plans;
2) Coordination and deployment planning;
3) Training and upgrading:
4) Infrastructural and logistical measures, such as emergency accommodation, etc and stockpiling food and drugs;
5) Establishing and/or strengthening local and national disaster protection structures and rescue services;
6) Disaster protection exercises;
7) Early warning systems.

Preparedness and prevention measures also include designing and implementing risk transfer concepts.



Hazard analysis	Vulnerability analysis		Disaster prevention and mitigation	Preparedness for disaster
Geographical analysis: • Location • Extent Temporal analysis: • frequency • duration • probability of occurrence Dimensional analysis: • scale • intensity	Geographical analysis: • Location • Extent Temporal analysis: • frequency • duration • probability of occurrence Dimensional analysis: • scale • intensity	Analysis of self-protection capabilities Development of strategies and measures at different levels: • family • village • community	Planning measures Physical preventive measures Capacity building, creating institutional arrangements	Emergency plans Early warning systems Evacuation plans

Fig. 4.5 From Risk Analysis to DRM Measures

For further disaster management plan refer to National Disaster Management Guidelines on "Management of Landslides and Snow Avalanches".

5 METHODS OF SCIENTIFIC INVESTIGATION OF SLOPES AND LANDSLIDES

The investigation and characterization of surface as well as subsurface conditions form the core of landslide studies. The success of mitigation and management agenda of any landslide depends upon the quality of investigation carried out on that particular landslide site.

In case of new roads/corridors, the emphasis is on planning, at a stage where there is an opportunity to choose the most favorable location for the alignment involving lowest overall hazards and risk. The evaluation of terrain through investigations will lead to predict the problems or hazards which may likely to occur after construction and consequently suitable schemes or plans for mitigation and management of the indentified trouble areas can be taken up. But for an existing road network, the focus on effective slope maintenance programme, i.e. maintain the slopes at minimal economic cost and identifying slopes most at risk, and providing remedial measures to minimize or eliminate risk. The investigation should be comprehensive enough that appropriate corrective measures can be taken[58]. So investigation is the first step towards understanding the phenomena.

Landslide investigations should be designed with reference to four basic guidelines that have evolved over many years of experience:

- Most landslides or potential failures can be predicted if proper investigations are performed in time;
- The cost of preventing landslides is less than the cost of correcting the affected elements, except for small landslides that can be handled by normal maintenance procedures;
- Massive landslides that may cost many times the cost of the original facility should be prevented and
- The occurrence of initial slope movement can lead to additional unstable conditions and movements.

5.1 Investigation phases

The investigations of landslides have different phases[118] (as shown in **Fig. 5.1**). As already mentioned there are two different conditions (virgin areas i.e. where roads are planned but not constructed and non-virgin areas i.e. existing roads which are already affected due to landslides) requiring investigation. The purpose of investigation is different for planned and existing roads, although some primary phases of investigation are similar in both the cases.

- ➢ For the virgin areas, in case of proposed road construction, the susceptibility of terrain to landslides and probability of recurrence of such processes is determined; Refer to chapter IV for landslide susceptibility mapping.
- ➢ While in case of existing landslides on highways, investigation leads to identification of the factors, causes, mechanisms, etc; and design of preventive measures preferably innovative and cost-effective. It would also cover probability of recurrence of existing landslides and susceptibility of the terrain to new landslides in future. The landslide susceptibility procedure

as explained in the chapter IV is to be followed in both the cases as per requirement.

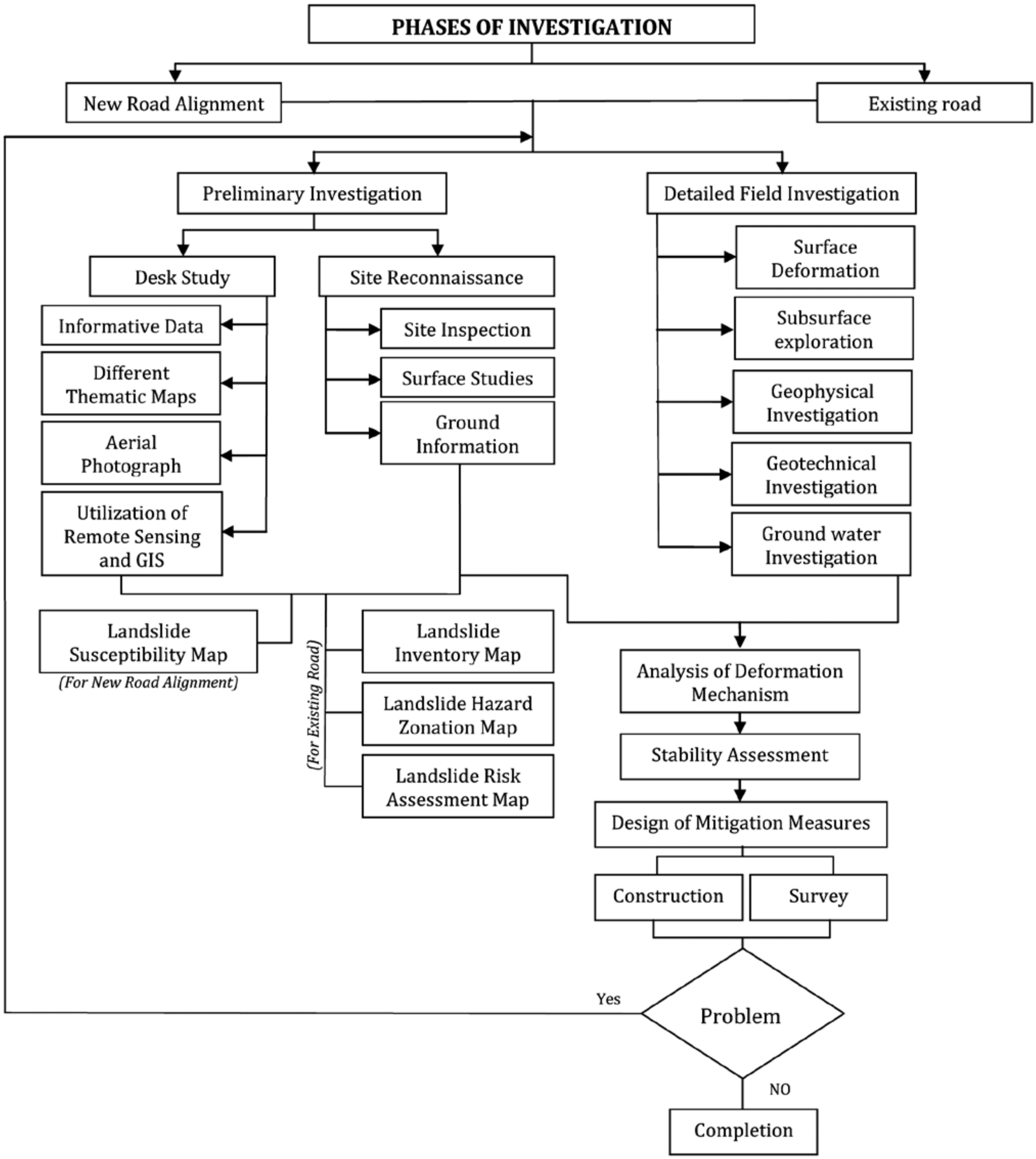


Fig. 5.1 Flowchart of Methodology Followed for Investigation of Landslides

5.1.1 *Preliminary Investigation*

The purpose of the preliminary site investigation is to establish the geological/geotechnical feasibility of the site and to determine the extent and precision of detailed surface/subsurface investigation required to obtain information needed for design and construction of control/ preventive mitigation measures. The preliminary investigation consists of two parts:

5.1.1.1 Desk study

The availability of desk study information, together with its scale and level of details, will determine the extent to which desk studies can advance feasibility studies prior to embarking on detailed fieldwork. The scope of desk study will depend on the availability and quality of available information's.

For detailed information on desk study and its parameters readers may refer to BSI BS 5930:1981 Code of practice for site investigations 2001. These phases are discussed in detail in Special Report 15, IRC State of the Art: Landslide correction technique.

5.1.1.2 Reconnaissance survey

The site reconnaissance may include both site inspection and local enquiries concerning existing and proposed features on and adjacent to the site. With an approximate understanding of the overall topographic feature and knowledge of the distinction(s) of movement and aerial extent of the slide, a detailed field investigation plan can be developed to delineate the aerial extent and a general direction of movement of the landslide zone, assess the geology and geologic structure, estimate the cause(s) of the sliding, and predict future movement.

For further consideration of reconnaissance survey for new roads refers to clause 7 of IRC:SP:19-2001 & **Clause 5.3** of IRC:SP:48-1998.

5.1.2 *Detailed Field Investigations and Mapping*

The field investigation is the central and decisive part of a study of landslides and landslide-prone areas[158]. With an approximate understanding of the overall topographic feature and knowledge of the distinction of movement and the extent of the sliding blocks, a detailed field investigation plan can be developed to delineate the aerial extent and a general direction of movement of the landslide zone, assess the geology and geologic structure, estimate the causes of the sliding, and predict future movement. A detailed investigation plan can be drafted to delineate the:

- ✓ Type of landslide, its size and mechanism
- ✓ Aerial extent of the slide, identification of the direction of deformation
- ✓ Location and shape of slide plane(s)
- ✓ Nature of landslide block(s)
- ✓ Possibility of further or future movement on slopes above the existing slide
- ✓ Distribution of ground water
- ✓ Type of soil in the site area

5.1.2.1 Some signs of slope movement

a) Tension Cracks on Roadway or on Slope above the Roadway

b) Escarpments in or above the Roadway

c) Sunken guardrail

d) Dips in Grade

e) Debris on Roadway

f) Bulge above, on, or below Roadway

Details are included in chapter II of the guidelines

5.1.2.2 Landslide hazard inventory, susceptibility, zonation and risk assessment

In landslide investigation use of inventory, susceptibility and zonation maps can cut the cost of road maintenance to a great extent. The utilization of these maps allows understanding the degree of vulnerability the terrain is having for landslide hazard and the location of existing landslides. This can help in optimizing the loss of construction of road, reduction in cost and time for maintenance after construction; reduce risk to life and property etc.

For further description of above topic refers to chapter four "Landslide Hazard Mapping, Vulnerability and Risk Assessment".

5.1.2.3 Investigation of surface deformation

The investigation of surface deformation is conducted to define the boundaries of the landslide, size, level of activity and direction(s) of the movement, and to determine individual moving blocks of the main slide. Instrumentation used for the surface deformation investigation includes extensometers, ground tilt meters, and movement determination by survey methods including transverse survey, grid survey, laser survey from the opposite bank, movement determination by aerial photographs, and G.P.S. (Chapter VII gives detailed information about the types of instruments required for an investigation).

During this phase, a detailed identification of terrain conditions, geologic formations, buried stream beds, soil and rock formations need to be carried out with extensive use of aerial photography and remote sensing and other types of mapping like topographical maps, geological maps, geomorphological maps etc.

5.1.2.4 Geotechnical investigation

In order to conduct slope stability analyses and to design appropriate control measures for landslides, physical properties such as strength of slide plane, location and depth of slide plane and stable ground areas must be determined. The following tests are generally performed;

- ✓ Physical tests, Standard Penetration Tests (Refer to section 21.2.1 of Geoguide 2, Hong Kong, 1987: page 111),
- ✓ Soil mechanic tests (unconfined compression, tri-axial compression box shear, ring shear, and in-situ shear (refer to IS:7746-1991 for in-situ data sheet of shear test of rocks; IS:13047-1991; section 3.2 of chapter 12 of the TRB Special Report 247, Landslides; Investigation and mitigation). IS:11229-1985; IS:11593-1986 covers specifications for shear box used as an assembly for testing of soils. BIS (IS:13365-1998; IS:13365-1992; 13365;

1997) provide the procedure for determining the class of rock mass based on geomechanics classification system which is also called the Rock Mass Rating (RMR) system.

5.1.2.5 Subsurface investigation

Generally there are five types of field subsurface investigation methods:

1) **Disturbed sampling:** Disturbed samples are generally obtained to determine the soil type, gradation, classification, consistency, density, presence of contaminants, stratification, etc. **Clause 5.1 of IS:1892:1979** gives the types of samples and methods of sampling to be used for both soil and rock.

2) **Undisturbed sampling:** These samples are used to determine the in-place strength, compressibility, natural moisture content, unit weight, permeability, discontinuities, fractures, fissures of subsurface deposits. The various tests that are necessary for different phases of exploration are given in **Table 3**; IS:1892-1979 (Reapproved 2002). **Appendix E** of IS:1892: 1979 (reapproved 2002), gives an outline for handling and sampling of rock and soil samples. ASTM D420-87: presents the standard guide for investigating and sampling soil and rock.

3) In situ investigation: In situ methods can be particularly effective when they are used in conjunction with conventional sampling to reduce the cost and time for field work. In-situ tests are used to provide field measurements of soil and rock properties. The common in-situ tests performed are presented in **Table 5.1**.:

Table 5.1 Types of Tests and their Code of Practice

Type of tests	Codes of practice
Standard Penetration Test (SPT)	IS:2131-1963; AASHTO T 206; ASTM D 1586
Cone Penetration Test (CPT)	see IS:4968 (Part I)1976); IS:4968 (Part II)-1976 and IS:4968 (Part III)-1976); ASTM D 3441
Field Vane Shear Test (FVT)	IS:4434-1978; AASHTO T 223; ASTM 2573
Pressure Meter Test (PMT)	ASTM D 4719; No.FWHA-IP-89-008
Dilato Meter Test (DMT)	IS:12955 (Part 2):1990
Plate Load Test (PLT)	IS:1888-1971; ASTM D 1194

5.1.2.6 Geophysical investigation

Geophysical methods are used for prospection of landslide bodies, detection of discontinuities and shear surfaces, as well as for investigation of hydrological regimes. However gaps exist and wider application of geophysics in landslide research have been hindered for two reasons: geophysical methods provide images of geophysical parameters which are not directly linked to geological parameters required by geotechnical engineers and geomorphologists; and the overestimation of the quality and reliability of results among some geophysicists. The development of 2D and 3D geophysical techniques has aroused a growing interest for assessing the landslide volume, characterizing the physical properties of the landslide material and locating the groundwater flows within and around the slide.

Methodology for the measurement of subsurface conditions by seismic refractions and planning of the survey is given in IS:15681-2006. Appendix B of IS:1892-1979 (Reapproved 2002) gives an outline of electrical resistivity and seismic methods used. Refer to **Clause B.1 of Appendix B** of IS:1892-1979 (Reapproved 2002).

For detailed account about the methods of site exploration refers to “Code of practice for subsurface investigation for foundations are given in IS:1892:1979 (Reapproved 2002)”. Subsurface explorations should be carried out in two stages; preliminary and detailed as mentioned in IS:1892:1979 (Reapproved 2002).

Laboratory testing for soils: The geotechnical engineer should conduct sufficient in situ and/or laboratory testing to characterize the physical geotechnical parameters of the earth materials affecting the proposed development.

A method for various tests of soils and preparation of samples can be found in IS 2720 from Part I-41.

Laboratory testing for rocks: Table 5 of BS 5930:1981 gives the standard practice for laboratory tests on rock. Also **Table 9** of BS 5930:1981 gives a guide for identification of rocks for engineering purposes. Reference should be made to Section 6 BS 5930:1981 of chapter: Laboratory test on samples. The following codes of practice are given for laboratory testing of rocks.

- IS:9179:1979 Method for the preparation of rock specimen for laboratory testing.
- IS:13365: Part 1:1998 Quantitative classification system of rock mass - Guidelines: Part 1 RMR for predicting of engineering properties.
- IS:13365: Part 2:1992 Quantitative classification systems of rock mass- Guidelines Part 2 Rock mass quality for prediction of support pressure in underground openings.
- IS:13365: Part 3:1997 Guidelines for classification system of rock mass Part 3 Determination of slope mass rating (SMR).
- IS:8764:1998 Method of determination of point load strength index of rocks.
- IS:9143:1979 Method for the determination of unconfined compressive strength of rock materials.
- IS:9179:1979 Method for the preparation of rock specimen for laboratory testing.
- IS:9221:1979 Method for the determination of modulus of elasticity and Poisson’s ratio of rock materials in uniaxial compression.
- IS:10050:1981 Method for determination of slake durability index of rocks.
- IS:10082:1981 Method of test for the determination of tensile strength by indirect tests on rock specimens.
- IS:10782:1983 Method for laboratory determination of dynamic modulus of rock core specimens?

- IS:13047:1991 Method for determination of strength of rock materials in triaxial compression?
- IS:14448:1997 Code of practice for reinforcement of rock slopes with plane edge failure?
- IS:13372: Part 2:1992 Code of practice for seismic testing of rock mass Part 2 Between the borehole.

5.1.2.7 Ground water investigation

Investigation of ground water, which is a driving force of sliding, includes determining ground water level, pore water pressure, ground water logging, ground water tracing test, pumping test, water quality analysis, electricity survey, geothermal survey, and geophysical logging (electric logging and radioactive logging). Based on the results of the above measurements and tests, ground water control works can be planned and designed.

Different types of piezometers are explained in IS:7436 (Part I-1993); IS:8282 (Part II-1996); Section 20.2.3., 20.2.4., 20.2.5., 20.2.6 of Geoguide 2, Hong Kong., 1987 and their installation procedure is discussed in 20.2.7). Detailed information regarding groundwater level observations can be obtained from ASTM D 4750.

5.2 Enforcing Remedial/Control Measures

Identifying, the need for corrective works and remediation procedures is a critical component of any investigation report in order to prevent the initiation of future landslide from the unstable and weak geometry of the Relic of the slide. Measures should be provided in order to stabilize the slide and prevent the formation of other slides in the disturbed areas.

Chapter VIII is exclusively dedicated to remedial measures.

6 INSTRUMENTATION, MONITORING, FORECASTING AND EARLY WARNING OF LANDSLIDES

Instrumentation, monitoring, forecasting and early warning of landslides empower individuals and communities to respond timely and appropriately to the hazards in order to reduce the risk of death, injury, property loss and damage.

Monitoring provides means of accurately and objectively gauging the stability conditions of unstable or potentially unstable slopes; it can also play an important role in assessing risk. Landslide monitoring includes the comparison of landslide characteristics like areal extent, speed of movement, surface topography and soil humidity from different periods in order to access landslide activity[149]. Long-term risk monitoring to identify developing trends and provide early warning information. Monitoring and predicting systems, when associated with communication system and response plans, is considered early warning systems (EWS)[49] (See **Fig. 6.1**). The capacity to observe, predict landslides and map vulnerabilities requires a huge technological investment in observing networks, forecasting systems, monitoring instruments, communication and dissemination platforms and modern sensors. Therefore only selective landslides of critical nature are required to be identified and monitored.

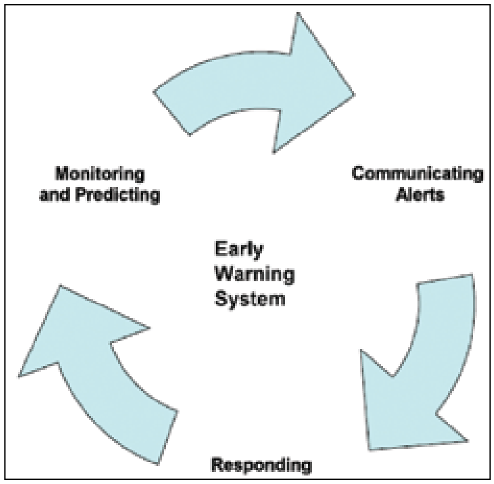


Fig. 6.1 Early Warning System Operational Aspects

6.1 Objectives of Instrumentation, Monitoring, Forecasting and Early Warning

- Determining the depth, shape, rate and scale of slope/ground movements so that calculations can be made to define the appropriate strength parameters at failure and design remedial treatments.
- Monitoring of the activity of marginally stable natural or cut slopes and identification of effects of construction activity or precipitation.
- Monitoring and evaluation of the effectiveness of various control measures[171].
- To take action to protect or reduce loss of life or to mitigate damage and economic loss, before the disaster occurs.
- Primary objective of a EWS is to empower individuals and communities to respond timely and appropriately to the hazards in order to reduce the risk of death, injury, property loss and damage[178].

6.2 Why and Where the Instrumentation

The increasing trend of the landslide incidences and recurrences along the highways is quite alarming and raise concerns regarding the stability of landslide prone areas along these highways and their potential impact to the safety of the travelling public, infrastructure, their property and environment. There are many major landslides along the Highways which are critical in nature and recurring every year. Thereby not only disrupting communication but also in many instances killing people. Many of such landslides are source of continuous trouble for the travelling public as well as the inhabitants. In addition to that these slides act as a bottleneck at the time of dire need during any disastrous situation where evacuation and early response is key to successful disaster management. Such identified critically known landslides should be monitored suitably for early warning to take timely steps to avoid, life loss, property and hardship on long traffic closures etc. The information about forecasting of the critical landslides should be integrated with the web server so that the same is available to all concerned to avoid risk and danger to public as well as alarm to the communication and transportation managers.

6.3 Techniques of Monitoring Landslides

Monitoring of landslides can be done in 3 ways:

- Measuring inherent factors like strength and stress parameters of slope masses.
- Measuring external factors like earthquake vibrations, rainfall and climatic conditions.
- Measuring strains, displacements, or release of energy due to slope movements or failures.

6.3.1 *Step Required in Monitoring of Landslides*

- Selection of specific location depending upon the type of movement, location, hazard and risk value of slope failure.
- Selection of monitoring methods and frequency of data collection.
- Data processing and methods/instruments of presentation of results.

6.3.2 *Surface Monitoring*

Surface movement may be horizontal or vertical. Horizontal movements are measures with surveying methods. This primarily involves distance measurements. Vertical movements are measured with settlement gauges. Surface methods to measure development of cracks, uplift and subsidence include repeated conventional surveying and installation of instruments to measure movements directly. Deformation measurement on surface of entire slope indicates existence of instability. Geotechnical and geophysical equipments used in surface/subsurface deformation are discussed in **Annexure 1 Table 8**.

6.3.2.1 Surveying methods and equipments

Surveying methods (**Table 6.1 & Annexure 1 Table 4**) are generally used for monitoring the magnitude and rate of vertical and horizontal movement of the ground surface, structures, and accessible parts of subsurface instruments. Two basic methods for the design of a deformation survey can be used:

- A horizontal or vertical control network is established in the area under investigation with control points located in the deforming region[154].
- Geodetic Surveying: Several surveying methodologies are used to investigate the activity of existing landslides. Two main classes are identifiable: point based (Total Station, GPS) and area based techniques (Photogrammetry,

Laser Scanning and Remote Sensing, in particular spaceborne radar interferometry). The geodetic methodologies like triangulation and distance measurements with electronic instruments permit a very high accuracy. By means of GPS (Global Positioning System) or Total Stations it is possible to detect movements on the order of mm/yr or cm/yr, and estimate the boundary of the landslide area. There are also several promising Remote Sensing techniques used to generate DEMs for landslide monitoring and characterized by high level of accuracy, in particular the new generation of high-resolution satellite imagery and mostly Interferometric SAR (Synthetic Aperture Radar). Photogrammetry is the technique most commonly used for this kind of survey, permitting to reconstruct the three dimensional landslide shapes with great wealth of information and to study its 3D. evolution over time. The development of digital photogrammetry offers today new possibilities and innovative procedures, like the creation of DSMs (Digital Surface Model) in automatic mode for the reconstruction of surfaces and the generation of orthoimages.

Table 6.1 Type of Surveying Techniques

Surveying Methods/Techniques	Result	Typical Range	Typical Precision
Precision tape	distance change	< 30 m	0.5 mm/30 m
Rod for crack opening	distance change	< 5 m	0.5 mm
Offsets from baseline	coordinates differences (2D)	< 100 m	0.5-3 mm
Triangulation	coordinates differences (2D)	300-1000 m	5-10 mm
Traverse/Polygon	coordinates differences (2D)	variable, usually < 100 m	5-10 mm
Leveling	height change	variable, usually < 100 m	2-5 mm/km
Precise leveling	height change	variable, usually < 50 m	0.2-1 mm/km
Electronic Distance Measurement (EDM)	distance change	variable, usually < 1-14 km	1-5 mm + 1-5 ppm
Terrestrial photogrammetry	coordinates differences (3D)	ideally < 100 m	20 mm from 100 m
Aerial photogrammetry	coordinates differences (3D)	H flight < 500 m	10 cm
Clinometer	angle change	+_10 degree	+_0.01-0.1 degree
Precision Theodolite	angle change	variable	+_10
GPS Survey	coordinates differences (3D)	variable	2-5 mm + 1-2 ppm
Total station (Leica geosystems)	coordinates differences (3D)	3500 m	1 mm + 1 ppm
RTK DGPS	coordinates differences (3D)	variable	+_ (5 mm + _2 ppm)
Terrestrial Laser Scanning (TLS)	coordinates differences (3D)	upto few 100 m	0.6 to 15 mm

Central Road Research Institute (CRRI) instrumented and monitored over eight decade old Kaliasaur landslide, which is still active and causes considerable damage to highway and risk to the commuters. To measure the movement of the landslide, 75 nos. of specially designed steel pedestals have been installed in preselected locations within the slide body and adjacent area[84]. Their original position was recorded using DGPS (Differential Global Positioning System) and TS (Total Station). Subsequent monitoring with DGPS and TS was done. It was noticed that the pedestals installed within the slide boundary did not move much except at only few locations. These locations were on the loose debris mass and rest of the pedestals which, have shown movement were located near and around the crown part indicating the movement only above the crown. Monitoring results when matched with field condition indicated surficial movement from the crown part. These results coincide with the activity of slide observed mostly from above the crown part. At that stage sufficient warning was passed to take immediate measures before the coming monsoon season.

6.3.2.2 Monitoring through remotely sensed methods

New tools of mapping like Earth observation satellites and remote sensing are able to provide significant information for mapping the extent and properties of landslides. The powerful In SAR (Interferometric Synthetic Aperture Radar) tools, which provide accurate topography and motion maps, can make significant contributions to the assessment and mitigation of landslide hazards[154].

- Interferometric SAR, whether satellite or ground-based (InSAR and DInSAR (Differential Interferometric SAR)) are the techniques most used for slope motion monitoring.
- Optical and infrared regions of the spectrum are used for monitoring purposes using high resolution images like IKONOS and QUICKBIRD, multi-temporal aerial photogrammetry.
- Space and air-borne microwave applications for monitoring movement using SAR interferometry from satellites like the Radarsat, ERS (European Remote Sensing), Envisat ASAR (Advanced Synthetic Aperture Radar) or forthcoming Terra SAR-X, ALOS (Advanced Land Observing Satellite), and Cosmo (Constellation of small Satellites for the Mediterranean basin Observation)/Skymed.
- Ground based differential SAR interferometry.
- Visual interpretation of aerial photography is still the most commonly used technique to support the elaboration of landslide inventories and also commonly used to reconstruct the evolution of landslide over time.

The contribution of remote sensing to the mapping, monitoring, spatial analysis and hazard prediction of mass movements has largely been in the form of stereo air photos and satellite images interpretations of landslide characteristics (e.g., distribution and classification) and factors (e.g., slope, lithology, geostructure, landuse/land cover, rock anomalies). Refer to **Table 5 of Annexure 1** for information of types of microwave satellites.

6.3.3 *Subsurface Monitoring*

Subsurface deformation measurements is required if sliding occurs and depth of sliding is not apparent from surface measurements and visual observations. Subsurface measurement includes horizontal deformation, vertical deformation and groundwater pressure which normally are required. Measurements of subsurface horizontal deformation provides basis for effective safeguard, install monitoring instruments that can identify mechanism of movement and any time-related change of stability-affecting factors[36].

Primary instrument for monitoring lateral, subsurface deformations is the inclinometer, rod extensometer, the details of which are given in **Table 6.2, 6.3 and 6.4**.

Table 6.2 Instruments for Monitoring Vertical Deformation are Single and Multi Point Instruments

Instrument System	Profile	Reading Time	Remote Access	Data Logging	Main Advantages	Main Limitations	Main Cost of Installation	On-Going Costs
Traversing System	Yes	45 minutes per 100 feet	No	No	Least expensive way to monitor many installations.	Probe cable and readout are bulky and heavy. Reading takes time.	Borehole for inclinometer casing is the main cost.	Sending a technician to read the installation is main cost.
Place Systemc	No	Seconds	Yes	Yes	Only way to obtain near real time readings and remote readings.	Long horizontal runs of cable must be protected from electrical transients.	Borehole for inclinometer casing is the main cost.	Few ongoing costs.

6.3.4 *Monitoring of Groundwater*

Monitoring of ground water, which is a driving force of sliding, includes determining ground water level, pore water pressure, ground water logging, ground water tracing test, pumping test, water quality analysis, electricity survey, geothermal survey, and geophysical logging (electric logging and radioactive logging)[118]. Based on the results of the above measurements and tests, ground water control works can be planned and designed.

Monitoring of pore water pressure is essential for effective stress analysis of the slide prone area. Pore pressure measurements are required especially around the failure plane for control measures to be adopted as well as for mitigating potential slides. The installation of a suitably placed piezometer is however preferable as the information obtained is more easily interpreted. Piezometers are instruments installed in the ground to measure pore-water pressures. Commonly used for landslide monitoring applications; standpipe, pneumatic, and electric.

Refer **Annexure 1 Table 6 and 7** for different types of piezometers and the factors on which they should be selected.

For detail description of piezometers refer to IRC Special report 15 “State of the art: Landslide Correction Techniques”

Table 6.3 Comparison of Single Point Systems

Instrument System	Range	Accuracy	Duration	Remote Access	Data Logging	Main Advantages	Main Limitations	Main Cost of Installation
Settlement Cell	10s of feet	Inch	Typically short term	Yes	No (Pneumatic cell) Yes (VW cell)	No interference with construction activities.	Reservoir must be higher elevation than cell.	Components cell is generally not installed in boreholes.
Settlement Point	1 to 2 feet	Fractional inch	No restriction	No	No	Simple	Pipe obstructs activities.	Borehole. If constructed through fill, components are main cost.
Rod Extenso meter	2 to 4 inches	Thousandths of inch	No restriction	No (mechanical head) Yes (electric head)	No (mechanical head) Yes (electric head)	High resolution measurements	Small range.	Borehole.
Settlement Extenso meter	25 inches or more	Hundredths of inch	No restriction	Yes	Yes	No interference with construction activities.	More expensive than other systems	Borehole.

Table 6.4 Comparison of Multi-Point Systems

Instrument System	Monitor	Range	Accuracy	Remote Access	Data Logging	Main Advantages	Main Limitations	Main Cost of Installation
Sondex	Vertical Profile	Large deformations	Fractional inch	No	No	Works with inclinometers	No remote reading	Borehole for inclinometer casing.
Magnet Extenso-meter	Vertical Profile	Large deformations	Fractional inch	No	No	Works with 1" pipe or inclinometer	No remote reading	Borehole for inclinometer casing or access pipe.
Rod Extenso-meter	Vertical Profile	2 to 4 inches	Thousandths of inch	No (mechanical head) Yes (electric head)	No (mechanical head) Yes (electric head)	High resolution measurements	Small range	Borehole
Horizontal Inclino-meter	Horizontal Profile	25 inches or more	Fractional inch	No	No	Monitors settlement over a broad area	Friction becomes factor in lengths over 300 feet Expensive	Trench or borehole.
Horizontal In-Place Inclino-meter	Horizontal Profile	25 inches or more	Fractional inch	Yes	Yes	Monitors settlement in critical areas.	Expensive	Trench or borehole. Components can be expensive.

6.4 Planning of instrumentation

Adequate planning is required before a specific landslide is instrumented. The plan should proceed through the following stages[171]:

- Identification of landslides to be monitored its purpose and outcome expected.
- Determination of types of measurements required and selection of the specific types of instrument best suited to make the required measurements;
- Definition of the location and depth of instrumentation and number of instruments;
- Development of the data acquisition techniques (manual, online) and
- Decision as to the management and presentation of the data acquired

6.4.1 *Instrument Selection, Installation, Monitoring and Interpretation*

In field instrumentation monitoring, plans are developed to select and install the appropriate instrumentation (**Table 6.5** gives various parameters on which instruments are selected and used.) and collect and interpret the data. This step is often the most difficult to accomplish.

Table 6.5 Various Parameters on which Instruments are Selected and Used

Concerning elements	Description
Critical parameters	When the parameters are identified, the specification for instruments should include the required range, resolution, and precision of measurements.
Complementary Parameters	The behavior of a soil or rock mass typically involves not one, but many parameters. In some cases, it may be sufficient to monitor only one parameter, but when the problem is more complex, it is useful to measure a number of parameters and to look for correlation between the measurements.
Ground Conditions	Ground conditions sometimes affect the choice of instrument. For example, a standpipe piezometer is a reliable indicator of pore-water pressure in soil with high permeability, but is much less reliable in soil with low permeability. A better choice in this case would be a diaphragm-type piezometer.
Environmental Conditions	Temperature and humidity also affect instrument choice. Instruments such as hydraulic piezometers and liquid settlement gauges have limited use in freezing weather. In tropical heat and humidity, simple mechanical devices may be more reliable than electrical instruments.
Data Acquisition	An automatic data acquisition system may be required when there is a need for real-time monitoring and automatic alarms. If a data acquisition system is required, the choice of instruments should be narrowed to those that can be connected to the system easily and inexpensively.
Instrument Life	Are readings needed only during project or will they be needed for years afterwards? Instruments, signal cables, and protective measures should be selected accordingly.
Instrument Quality	The difference in cost between a high-quality instrument and a lesser-quality instrument is generally insignificant when compared to the total cost of installing and monitoring an instrument. For example, the cost of drilling and backfilling a borehole is typically 10 to 20 times greater than the cost of the piezometer that goes in it.
Instrument Performance	Instrument performance is specified by range, resolution, accuracy, and precision. The economical designer will specify minimum performance requirements, since the cost of an instrument increases with resolution, accuracy, and precision.

Type of instruments used in landslide monitoring is illustrated in **Figs 6.3** and **Table 6.6**. Note that any instrumentation scheme depends upon the site and is determined by investigations conducted in landslide prone area.

Table 6.6 Instrumentation and Accessories Generally used in Landslide Monitoring are as Follows (refer to Fig. 6.3)

No.	Instruments	Purpose
1	Inclinometer system	Monitoring lateral movement - inclinometer system with bi-axial servo accelerometer probe and data logger with storage capacity 30,000 readings. For settlement also, magnetic extensometer system
2	Piezometer	Monitoring of ground water level - vibrating wire piezometer. Standpipe piezometer with dip-meter water level sounder probe.
3	In-place inclinometer	Continuous monitoring of slope stability - In-place inclinometer bi-axial servo accelerometer probes
4	Centre hole load cell	Monitoring of tension in anchor.
5	Bore hole extensometer	Monitoring of movement inside a slope at various depths - Multiposition bore hole extensometer
6	Fixed tiltmeter	Monitoring of tilt on retaining walls or rocks that may topple -
7	Crack meter	Monitoring of displacement/opening in cracks
8	Stress meter	Monitoring of stress on interface of soil/concrete or soil/rock -
9	Rain gage.	Monitoring of rainfall
10	Flow measurement	Monitoring of seepage - seepage measurement system with sensor to measure thrust on submersible cylinder.

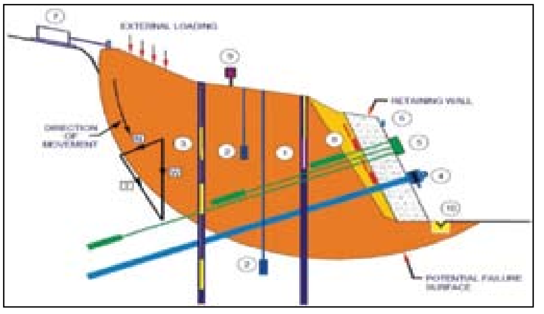


Fig. 6.3 General Instrumentation Scheme

6.4.2 *Reading, Recording and Data Transmission*

The frequency of reading will depend upon the situation and the nature of the changes which the instruments are being used to monitor. Any readings which indicate a marked change in conditions should be checked immediately. The calibration of some instruments can change with time and re-calibration may become necessary. Duplication of instruments in critical areas will aid the interpretation of readings[48]. All instrument readings should be plotted on a time base so the significance of variations can be assessed more easily.

Automated data recording and transmission can be undertaken in several ways, each reflecting different levels of automation, investment, and sophistication. This type of system requires periodic visits to the site to download the data. Remote data acquisition equipment includes:

- Datalogger
- Multiplexer
- Communication devices,

- Power source.
- In addition, specialized software is necessary to program and interact with the datalogger.

6.5 Developing Technologies for Monitoring Ground Movement[121]

- **TDR Cable:** Time Domain Reflectometry (TDR) is an alternative method of detecting ground movements that utilizes coaxial cables grouted within boreholes or embedded within fills or structures. Ground displacements deform the cable and change the travel time of an electrical pulse. In theory, the signal alteration through the deformed section also provides an approximate measure of the magnitude of displacement. The benefits of this system include simple–quick readout, remote monitoring and data acquisition, and ability to survive large ground deformations. A limitation is the inability to measure the direction of sliding and small rates of movement.
- **Digital Bluetooth inclinometer:** Digital inclinometer probes have recently been introduced by several manufacturers. Micro-Electro Mechanical Systems (MEMS) accelerometers are positioned within the inclinometer probe. MEMS are designed to integrate small sensors on a single chip.
- **Wireless In-Place MEMS Systems:** This type of instrumentation consists of a string of closely spaced MEMS accelerometers combined with an Automated Data Acquisition System (ADAS) that provides near real-time in-place monitoring.
- **Vibrating Wire Inclinometer:** These instruments are being developed for IPIs and other ground movement instrumentation.
- **Fiber Optic Inclinometer:** Fiber-optic sensors use light guided in the fiber to perform high-resolution measurements. The measuring core is flexible and contains an optical setup with mirrors. The fully symmetric internal structure of the inclinometer makes it insensitive to temperature variations that affect the whole measuring core.

Recently, Electromagnetic Pulse Radiation, a geophysical method for detecting landslide areas of the types sliding, spreading and flowing has been developed. It is based on the registration of natural electromagnetic emissions. The new method can be used on the surface and in boreholes to identify not only landslide areas but also volcanic and earthquake prone zones. The instrument, called Cereskop, can be operated by just one person. (Refer to: Krauter. E- New methods of investigation and controlling of landslides)

6.6 Prediction

Slopes which are already in movement, monitoring is often the only chance for a prediction[30]. The prediction accuracy for the location and size of the landslide event will continue to improve as more data is collected by the monitoring system.

Amrita Center for Wireless Networks and Applications provides a framework for Wireless Sensor Network (WSN), focused on is for purpose of detecting natural disasters[139]. WSN can be useful to disaster management in two ways. Firstly, WSN has enabled a more convenient early warning system and secondly, WSN provides a system able to learn about the phenomena of natural disasters. Wireless Sensors are one of the cutting edge technologies that can quickly respond to rapid changes of data and send the sensed data to a data analysis center in areas where cabling is inappropriate. WSN technology has the capability of quick capturing, processing, and transmission of critical data in real-time with high resolution. However, it has its own limitations such as relatively low amounts of battery power and low memory availability compared to many existing technologies. It does, though, have the advantage of deploying sensors in hostile environments with a bare minimum of maintenance. This fulfills a very important need for any real time monitoring, especially in hazardous or remote scenarios.

This landslide detection system using a WSN is the first in India, one of the first in the world of its kind. It is also one of the first landslide field deployments backed up by a laboratory setup and modeling software. The current system (**Fig. 6.4**) can be replicated in other rainfall induced landslide prone areas around the world.

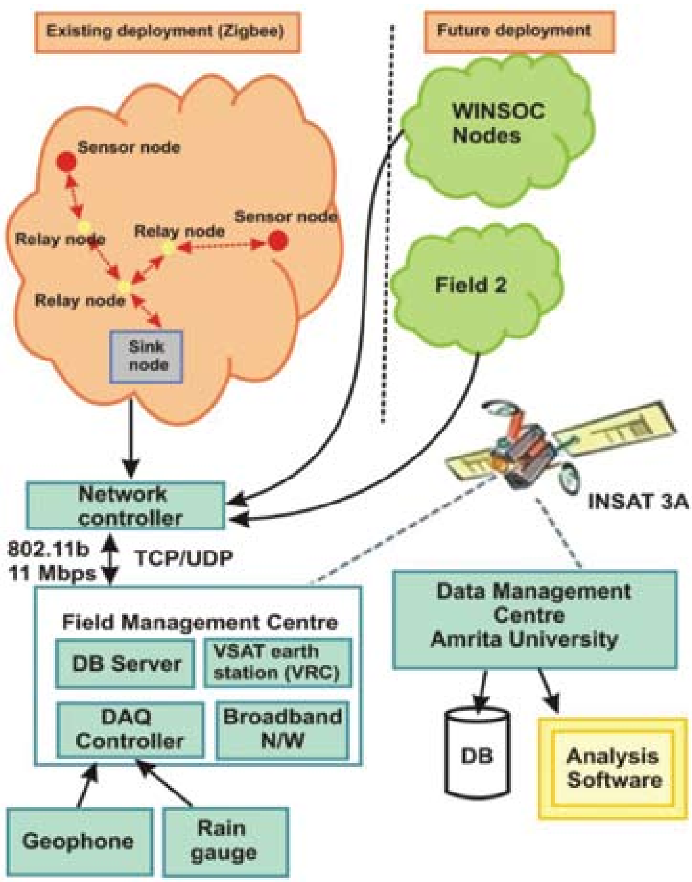


Fig. 6.4 Wireless Sensor Network Architecture for Landslide Detection

A new type of sound sensor system (**Fig. 6.5**) has been developed to predict the likelihood of a landslide. Developed by researchers at Loughborough University, in collaboration with the British Geological Survey, it works by measuring and analyzing the acoustic behavior of soil to establish when a landslide is going to occur so that preventive measures can be undertaken. Noise created by movement under the surface builds an increasing growth of loudness as the slope becomes unstable and so gauging the increased rate of generated sound enables accurate prediction of a soil collapse. The detection system consists of a network of sensors buried across the hillside or embankment that presents a risk of collapse. The sensors, acting as microphones in the subsoil, record the acoustic activity of the soil across the slope and each transmits a signal to a central computer for analysis.

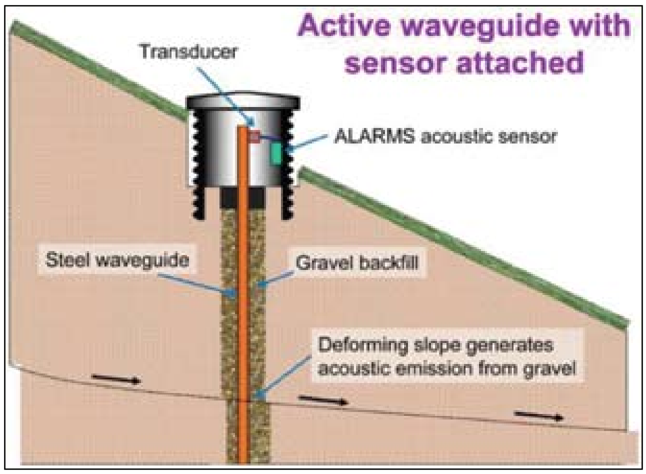


Fig. 6.5 A New Sensor for Early Warning of Landslides

This technique can also be used in monitoring the condition of potentially unstable slopes built to support transport infrastructure, such as rail and road embankments. The system is now being developed further to produce low cost, self-contained sensors that do not require a central computer. It is now focused on manufacturing of very low cost sensors with integrated visual and/or audible alarms, for use in developing countries.

Central Scientific Instruments Organization (CSIO), a laboratory of Central Scientific Industrial Research (CSIR) presents a case study of landslide monitoring and early warning of Mansa Devi (Haridwar), located at Haridwar by pass road. Data recorded by instrumentation network installed at Mansa Devi landslide site by five sensors (Rain Gauge, Inclinometer, Tiltmeter, Crack meter and Earth pressure cell) was analyzed and a relationship between rainfall intensity-surface parameters and landslide occurrence drawn with neuro-fuzzy approach for predation of landslide and concept of early warning system is also described. For further description refer to paper “Mittal et al 2011, Analysis of data using neuro-fuzzy approach recorded by instrumentation network installed at Mansa Devi (Haridwar) landslide site”.

6.7 Forecasting

In terms of time, forecasts can be roughly divided into three classes of lead time:

I. Long-term forecasts mostly indicate a potential hazard within a certain region, years before they actually occur.

First step towards a landslide forecast is a systematic collection of data in a landslide hazard zonation map[28]. An ideal map of slope instability hazard should provide information on the spatial probability, type, magnitude, velocity, runout distance and retrogression limit of the mass movements predicted in a certain area. These maps can be interpreted as first long-term forecast. Although, they cannot predict the exact time of an event and cover a region, rather than a specific slope, they indicate a potential hazard several years in advance of an event.

II. Mid-term forecasts predict failures several months ahead and

A routine survey of landslide prone areas or slopes provides information about the progress of unstable masses[28]. Routine surveys allow monitoring with lead times of years to months for mid-term forecasts.

III. Short-term predictions have a lead time of months to days

Digital tools such as Geographic Information Systems (GIS), Digital Image Processing, Digital Photogrammetry and Global Positioning Systems (GPS) are applied in forecasting landslides. Of late generation of Digital Elevation Models (DEM) obtained from different sources like Synthetic Aperture Radar (SAR) or Light Detection and Ranging (LIDAR) are also applied.

Forecasting the time of slope failure can be done by the following procedure

I. Measurement of the relative displacements of a slope across tension cracks or along the centre line, depending on field conditions.

II. Determination of the beginning of the unstable state of the slope through the relative displacement curve.

III. Calculation of the constant strain rate from the relative displacement curve.

IV. Estimation of creep rupture life corresponding to the strain rate, using the relationship between strain rate and creep rupture life.

6.8 Early Warning and its Importance

Early Warning (EW) is “the provision of timely and effective information, through identified institutions, that allows individuals exposed to hazard to take action to avoid or reduce their risk and prepare for effective response[49].”, and is the integration of four main elements (i.e. design, monitoring, forecasting and education) **Fig. 6.6**.

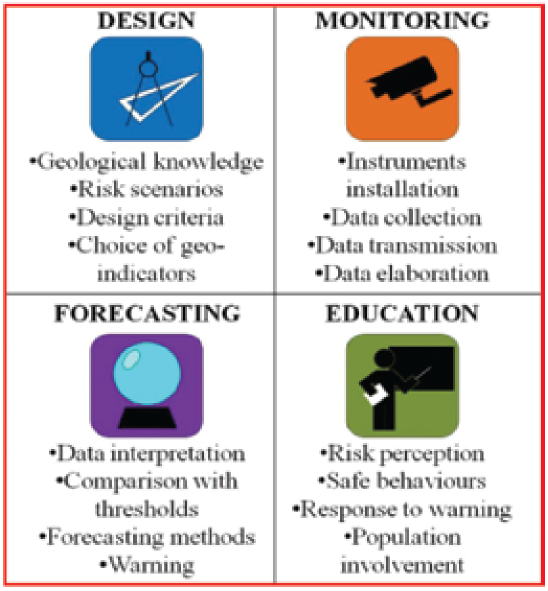
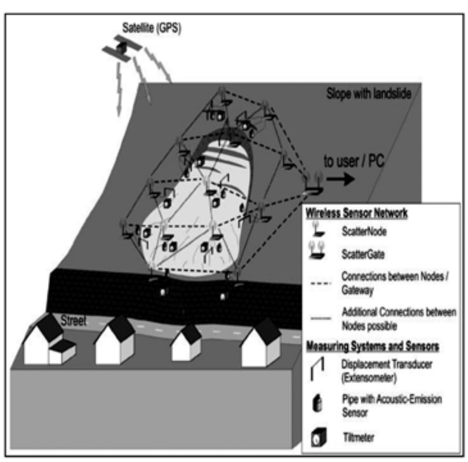


Fig. 6.6 Main Elements of Early Warning

6.8.1 *Early Warning Systems for Landslides*

EWS are based on either spatial warnings with to respect triggers and specifically to hydro-meteorological events, or on locally installed monitoring devices. These systems focus on the technical aspects of early warning and do not take into consideration the whole chain of early warning including monitoring, analysis, establishing alert thresholds, and issuing warnings and up to the societal responses including responsibilities. EWSs are extremely site-specific and may greatly vary depending on the scale, type of landslide, element at risk, etc[61]. Some of the early warning systems are described below:

1. **Wireless Sensor Networks (WSN):** WSN consist of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions, such as temperature, sound, vibration, pressure, motion or pollutants, at different locations. Each node in a sensor network is typically equipped with a radio transceiver or other wireless communications device, a small micro controller, and an energy source, usually a battery. *(Matthias Busslinger, 2009. Landslide time-forecast methods, A literature review towards reliable prediction of time to failure. HSR University of Applied Sciences Institut für Bau und Umwelt Rapperswil, Switzerland.)*
2. **The SLEWS (Sensor-Based Early Warning System) Fig 6.7:** It gathered data using wireless sensor networks via information processing and analysis to information retrieval for landslides and mass movements. It paid special attention to mobile, cost-reduced and easy deployable measurement systems, as well as the modern information systems under consideration of interoperability and service orientated architecture concepts. It focused on three sensor types measuring acceleration, inclination and pressure to monitor landslide initiation. *(Arnhardt, C et al. 2007. Sensor based Landslide Early Warning System-SLEWS. Development of a geo-service infrastructure as basis for early warning systems for landslides by integration of real-time sensors. GEOTECHNOLOGIEN Science Report. Early Warning Systems in Earth Management. Kick-Off-Meeting 10 October 2007 Technical University Karlsruhe, pp.75 - 88.)*



SLEWS: BASIC PRINCIPLES
Ad-hoc sensor network:
• Wireless
• Self deploying
• Simple installation
Sensor fusion:
• Cost reduced detector units
• Adaptable detector combinations
• Determine suitable measurement quality
Open spatial data infrastructure:
• Service oriented interfaces
• Modular
• OGC/SWE based
Customized information distribution:
• Arbitrary richness of detail
• Use of arbitrary communication channels

Fig. 6.7 Schema of a Wireless Sensor Based Landslide Early Warning System

3. Senslide is a low cost Landslide Prediction System based on Wireless Sensor Network WSN technique. The system consists of single-axis strain gauges connected to cheap nodes, each with a CPU, battery and a wireless transmitter. *(Sheth, A. et al. 2007. Senslide: A Distributed Landslide Prediction System. http://research.microsoft.com/en-us/groups/mns/senslide-osr2007.pdf)*

4. Wireless Sensor Columns includes four types of sensors: geophones, strain gages, pore pressure transducers and reflectometers as well as seismic sources placed at regular intervals over the length of the column for detecting early signals of landsliding. *(Matthias Busslinger, 2009. Landslide time-forecast methods, A literature review towards reliable prediction of time to failure. HSR University of Applied Sciences Institut für Bau und Umwelt Rapperswil, Switzerland.)*
5. Rocknet is a self organizing wireless sensor network used for rockfall surveillance and provides real-time warning. Wireless sensor nodes are equipped with accelerometers, temperature and other sensors. The nodes are distributed in a rockfall prone area. If a specified number of nodes recognize vibrations, an alert is released and for traffic can be stopped outside the danger zone. *(Matthias Busslinger, 2009. Landslide time-forecast methods, A literature review towards reliable prediction of time to failure. HSR University of Applied Sciences Institut für Bau und Umwelt Rapperswil, Switzerland.)*
6. Integrative Landslides Early Warning Systems (ILEWS) measures deformations using several different sensors in a wireless sensor network (web ScatterWeb). Geoelectrical survey systems are applied to examine the landslide body. *(Matthias Busslinger, 2009. Landslide time-forecast methods, A literature review towards reliable prediction of time to failure. HSR University of Applied Sciences Institut für Bau und Umwelt Rapperswil, Switzerland)*.

6.8.2 *Challenges of Early Warning Systems*

The key challenge in EWS is translating warning into concrete local action, even for those with effective capacities for forecasting, detecting and monitoring hazards and suitable technologies for disseminating advance warnings. Along with technical difficulties of landslide hazard prediction, legal, social and political dimensions add to the complexity of early warning. **Fig. 6.8** shows a basic framework for early warning system.

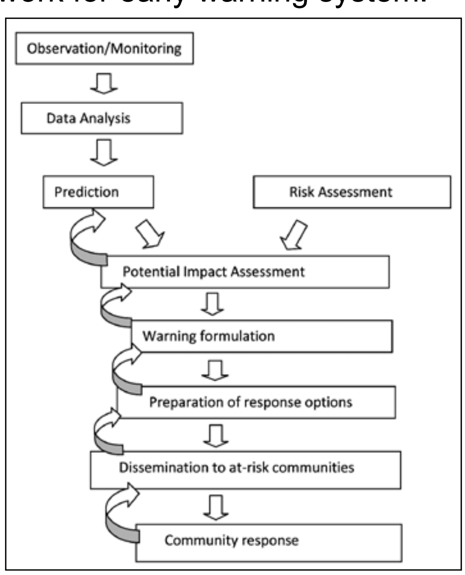


Fig. 6.8 Framework for Early Warning System

7 LANDSLIDE RISK REDUCTION THROUGH IMPROVED PLANNING, DESIGN AND CONSTRUCTION PRACTICES

The standard of good practices for landslide reduction and their management for effective planning, investigation, design and construction of projects that involve highway slopes and their maintenance is must.

7.1 Planning of Highways Projects

The problem of coping with slope hazards revolves around two questions:

- **On intended new road alignments**, how to minimize the incidence of potential damage from landslides. In this case, corridors or alignments need to be compared so that the route involving the lowest overall hazard can be selected. The emphasis is on planning, at a stage where there is an opportunity to choose the most favorable location for the alignment,
- **For an existing network**, how to manage a slope maintenance programme, i.e. maintain the slopes at minimal economic cost. Here, the focus is on identifying slopes most at risk, and measuring or monitoring an existing geotechnical asset.

7.1.1 *Planning of new Highway Projects*

7.1.1.1 Alignment selection

Planning of a new highway is a repetitive process which involves transport, highway, environmental, geological and geotechnical professionals. The purpose here is to find a safe alignment or review options for alignments. This involves defining potential hazardous zones in the landscape, avoiding them where possible or identifying appropriate design options where avoidance is not possible[116]. Decisions made at the route selection stage for highways may have long-term effects on road construction and maintenance costs, user safety, and other resources. Routes must be selected and located to meet the objectives of higher-level plans within the constraints of any approved operational plans or permits.

Most of the things required for above purpose are already mentioned in example every important details of pertaining to landslide and other mass movement.

The IRC:SP:20-2002, Rural Roads Manual & IRC:SP:48-1998, “Hill Road Manual” gives detailed guidance on selection of the alignment.

7.1.1.2 Report

The reconnaissance report should identify and or confirm:

- Terrain conditions and road sections that are in unstable or potentially unstable terrain.
- Control points and topographic features (e.g., rock bluffs, swamps, avalanche paths, landslides, and debris slides), including those that may be used as photo ties.

- The sections of road that encroach on public utilities.
- All continuous and intermittent drainage flow channels, springs, seeps, and wet areas.
- Riparian areas.
- Forest covers (species composition, timber quality, and volume per hectare).
- Recommended slash and debris disposal methods and additional clearing widths required for the slash and debris disposal.
- Soil types based on visual observations of exposed cuts, shallow hand dug test holes and probing, and the location of these soils on maps or aerial photos (see Appendix 1 for a method of identifying soils).
- Maximum road grades and minimum curve radii.
- Location and extent of bedrock, if rippable, and the potential as ballast.
- Location and extent of gravel sources and the potential for use as subgrade and surfacing materials.
- Geological details encompassing type of lithology, their stratigraphic sequence, structural setup such as faults/thrust/joints/fractures etc.

7.1.1.3 Survey level selection

There are two general types of surveys: a field traverse and a location survey. To determine which survey type and level to recommend in the reconnaissance report, the physical characteristics of the terrain, design complexity, and desired road prism geometry should be considered.

7.1.1.4 Road plans to mitigate slope hazard

In areas of complex geology a balance has often to be achieved between what is theoretically desirable in terms of frequent design variation along an alignment and the practicalities of construction and cost. A pragmatic approach is to develop a few standard, generic slope designs for costing purposes, knowing that these will be modified in the light of information recovered when the ground is opened up during construction[116].

7.1.1.5 Criteria for measures to maintain slope stability

If a proposed road will cross areas with a moderate or high likelihood of landslides, the measures to maintain slope stability must be prepared by a qualified professional. The recommendations should be site specific and precise so that the road designer cannot misunderstand them. He or she should also provide the results of the measures to maintain slope stability as they apply to the road prism, or adjacent to the road prism, separately from other recommendations.

It must include measures to maintain slope stability that satisfy either:

- **Criteria 1 (hazard-based)** – In these criteria, the selected measure is the least likely measure to result in a landslide, and the qualified professional provides a statement to this effect.

- **Criteria 2 (risk-based)** - In this criteria, the selected measure is based on an analysis (i.e., landslide risk assessment) made by a qualified professional.

7.1.1.6 Geotechnical Review

It is mandatory to carry out some form of geotechnical review for planning of new highway/ alignment as it will help in identifying the landslide hazard and critical issues that can influence a highway project. Geotechnical review provides relevant information on:

- Scope of the geotechnical work,
- Cost and time requirements, for investigation, design , construction and maintenance of the geotechnical work,
- Hazard mitigation measures, land-take, cost, programming, professionals required for investigation, design, construction and maintenance of the chosen route alignment.

In Geotechnical Review, following tasks is to be carried out:

STEP 1:

1) Search for, obtain and study;
   - i. Information relevant to the project from all potential sources including the landslide database, landslide inventory maps, boulder inventory maps, records of annual rainfall and landslide reports, landslide study reports etc.
   - ii. Relevant past site investigation records, geotechnical design reports and construction reports.
   - iii. Published geological maps.
   - iv. Relevant services and utilities records.
   - v. Study the most recent set of topographical maps and at least two sets of good quality of aerial photographs (Refer to IRC:SP:48-1998).
2) Carry out a detailed walkover survey of the proposed alignment(s) and nearby to:
   - Prepare records on key natural terrain and man-made geotechnical features, paying attention to recording any signs of ground instability and landslide hazards.
   - Undertake the necessary topographical survey (IRC:SP:48-1998), geological, geomorphological and seepage mapping.
3) Assess the general topographical, geological hydrological and groundwater conditions along the proposed highway corridor as outlined in IRC:SP:48-1998 and refine the project boundaries.
4) Carry out a Natural Terrain Hazard Review.
5) Identify all existing man-made slope features along the tentative alignment and nearby that could affect or be affected by the proposed highway, determine their date of construction where possible.

6) Carry out a preliminary assessment of the site conditions and the identified landslide hazard that could significantly impact on the cost and programming of the project, in particular :

- Assess the impact of the potential landslide hazard from natural terrain (e.g: boulder falls), determine the extent of the terrain that needs to be further assessed and outline the likely mitigation strategy required.
- Determine the safety standard for all of the existing man-made slope features based on the anticipated use of the highway and outline the necessary investigation and assessment of their stability or the likely landslide preventive works required to upgrade the features to the current safety standard.
- Identify any new man-made slope features that are will likely be formed and determine the required design standard.
- Prepare a preliminary report of ground investigation works.

7) Based on the above work:

- Assess how the identified geotechnical features, hazards and constraints may affect the proposed highway alignment and recommend adjustment of the corridor, if it is considered necessary.
- Identify the contractual and construction management issues (e.g. supervision, design review, traffic constraints, safety of road users, blasting control, etc) related to the likely geotechnical work and landslide mitigation measures.
- Provide preliminary estimates of the potential costs, programming and geotechnical personnel requirement for the investigation, design and construction of geotechnical works.

STEP 2:

Based on the available information carry out a comparative assessment of the alternative corridor/alignment in particular;

- Rank the alternatives based on the magnitude of the geotechnical hazards present along each proposed corridor/route.
- Recommend the appropriate rating to be applied for use in a balanced evaluation of the geotechnical factors with other factors where such evaluation process is required.

STEP 3:

A review report should be produced documenting the work done, the information examined, the findings and recommendations, schematic plans and cross sections at critical locations of the geotechnical works and landslide hazard mitigation measures to be proposed for the project. The report shall also include a hazard map showing the corridor alignment, the source and area extent of all landslide hazards identified, the details of all existing slope features including those to be upgraded and new slope features to be formed under the project, the principal drainage courses and the probable direction of and limits of travel of any landslide debris from natural terrain.

7.1.1.7 Critical sites

More intensive assessment of ground conditions is required where an alignment is forced to cross areas that are known to be unstable or marginal, to ensure that the route is adequately protected while not wasting money on over-elaborate protection in a situation where the risk of damage or loss is high.

In this situation a detailed landslide hazard map at a suitable scale of the zone needs to be made, in order to indicate the hazardous parts where slope protection measures and special design considerations for the carriageway are required. Slope monitoring may be appropriate at specific locations, to measure, for example, the rate of slope movement, landslide recession or erosion[116].

7.1.2 *Planning for Existing Highways*

Primary concern for the highway slopes is the stability of the slopes. Scope of planning for existing highways can vary widely, ranging from upgrading of a road to local improvements of a road's alignment like widening.

As compared with a new highway, planning of a road upgrading or a widening project is generally more constrained by existing structures, services and utilities and the surrounding topography. The need to maintain traffic flow during construction is also an important constraint. The selection of appropriate route alignment and/or design options should take into account these constraints[56].

7.1.2.1 The objectives of planning for existing roads

- minimize the risk and severity of road accidents that may result from landslide hazards,
- minimize the need for remedial work,
- reduce the life cycle costs of the project,
- improve the awareness of safe design practices of everyone involved in the design.

Where there is a large number of failures on a network, an inventory can help in establishing a priority for earthworks most likely to fail, or most likely to constitute the greatest risk. Once a database of relevant slope information has been established and analysed, then updating of the database can be focussed on those datasets that are both key to the slope condition and are likely to change within engineering time. The inventory can provide a tool to:

- Plot the location of the earthworks, along the length of the route or network.
- See where the slope failures are, and describe and classify them.
- Rank the earthworks in order of priority for repair.
- Calculate an order of cost for the repairs.

The limitation of a slope inventory is that the data give information only on the slopes measured. There is no information on the slopes in the landscape at large; inventory is not an ideal tool for extrapolation unless combined with terrain evaluation, as was done in Indonesia. If used within the framework of a terrain classification, the two together form a powerful tool for planning, management and design.

7.1.2.2 Planning for monitoring of key sites

For important slope hazard sites such as major cuttings, valley side traverses or stacks of climbing loops the cut slopes can be measured to assess the hazard (**Table 7.2**), or kept under continuous observation by monitoring. It would be appropriate to make a detailed geotechnical assessment of an important slope that is felt to pose a risk (**Fig. 7.1**). Planning for existing highways is the same order as followed in IRC:SP:48-1998, with the addition of a few measures which can be included in the planning process.

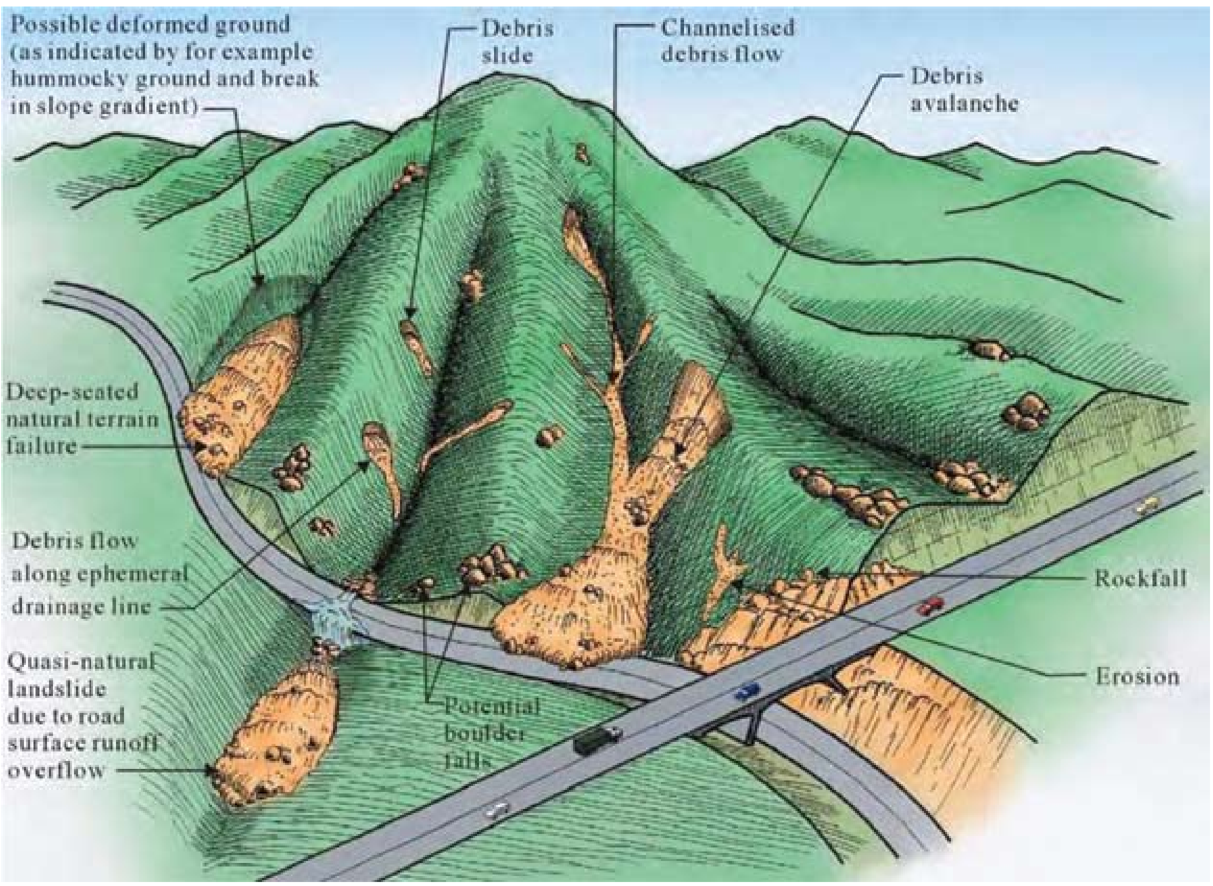


Fig. 7.1 Natural Terrain Landslide Hazards Posed to a Highway

Table 7.2 Geotechnical Hazards that Needs to be Considered for a Highway Project

1.	Existing man-made slope features that could affect or be affected by the project
2.	Man-made slope features that will be formed along the route (cut slopes, fill slopes, retaining walls)
3.	Natural terrain landslide hazards (debris avalanches, debris slides, rock fall, gully erosion)
4.	Other geotechnical hazards (eg: presence of soft ground, karstic areas)
5.	Hazards associated with the geotechnical works (rock blasting, excavations, diversion of surface water)

Where landslides or slope failures occur, there is often a need to identify quickly the likely cause of the failure and to develop short or long term measures to mitigate the failure. Planning required for dealing with these hazards can be summarized into[145]:

1. Simple field reconnaissance to in-depth topographic survey as outlined in IRC:SP:48-1998.
2. Field data collection.
3. Geotechnical section must provide oversight during repair of the landslide or slope failure, particularly if an emergency condition is identified. This can range from documenting work done by sub-contractors to conducting analyses to help decide the type of repairs that should be implemented. This will require:
   - Close communication with the contractor who is performing the repair.
   - Having a clear understanding of responsibilities and expectations during the work.
   - Providing good documentations of decisions that are made, including photographic documentation,
4. Slope stabilization methods : If the results of the stability analyses indicate that the roadway slope does not meet the minimum factor of safety requirements or displacement limits, than it may be necessary to use slope stabilization methods to improve the slope performance, mentioned in chapter VIII of this guidelines and also in IRC:SP:48-1998.

Where a site shows signs of being at risk but for reasons of size or complexity are felt to be too expensive to protect, monitoring can be implemented to detect any sudden change in condition. In extreme cases an early warning system can be installed to give warning of imminent failure and have the road closed before the slope gives way.

7.2 Hazard Assessment

There is a wide range of approaches to hazard assessment and these approaches can have very different applications:

a) **New Roads construction:** the primary task is to locate an alignment that minimises the hazards likely to affect the road. This involves examining a large area of terrain in a broad way. This strongly indicates a terrain evaluation approach to the assessment (chapter IV of the guidelines).

b) **Existing Roads:** for an existing alignment or network, the engineer may require detailed design information for specific slope hazards. A numerical approach is more likely to be appropriate in this situation (chapter IV of the guidelines).

Geomorphological mapping and walk-over geotechnical mapping are based on the premise that the landscape bears visible indicators of past instability, from which future activity may be predicted. Land forms such as concave slopes, fans, terraces and slopes with thin soil cover are indicators of particular kinds of land-forming process including instability, and are interpreted to form a picture of how the land has evolved into its present state and how it will evolve in future.

Geomorphological mapping therefore provides the engineer with a valuable tool to separate areas of stable terrain from those that are unstable, and appreciate what processes may affect the road in the short and longer term (Chapter V of the guidelines).

7.3 Technical Tools for Road Alignment

In the absence of a GIS computerized system, transparencies can be made of each map and then can be overlaid together[4]. It is important that the maps and data be at the same scale. The following list describes many types of information that might be useful in constructing layers for GIS analysis of landslide potential.

- **Topographic Map**- Indicates slope gradient, terrain configuration, drainage pattern.
- **Terrain Map**-Identifies material, depth, geological processes, terrain configuration, surface and subsurface drainage, slope gradient (also called surficial geology or Quaternary geology maps).
- **Bedrock Map**- Identifies bedrock type, surface and subsurface structure, surficial cover (overburden), and age of rock over a topographic map base.
- **Engineering Soil Map**- Identifies surficial material type, drainage, limited engineering characteristics, soils characteristics, vegetation cover.
- **Forest Cover Map**- Identifies surface vegetation, topographic features, surface drainage pattern, and in some cases, soil drainage character.
- **Research Studies**- May provide information on all of the above, plus quantitative data on controlling factors and possibly local stability risk assessment.
- **Aerial Photography Remote Sensing-** Identification can be made of:
    - vegetation cover,
    - topography,
    - drainage pattern,
    - soil drainage character,
    - bedrock geology,
    - surficial geology,
    - landslide type, and relationship to other factors.
- **InSAR Imaging**- InSAR is an acronym for Interferometric Synthetic Aperture Radar. Most InSAR equipment is able to penetrate fog and rain and can be used in areas difficult to access by foot. By bouncing signals from a radar satellite off the ground, digital elevation model (DEM) maps can be produced that will show the ground terrain. Ordinary radar on a typical Earth-orbiting

satellite has a very poor ground resolution of about 3 to 4 miles because of the restricted size of the antenna on the satellite.

- **LiDAR Imaging**- LiDAR is an acronym for Light Detection and Ranging, also known as ALSM or Airborne Laser Swath Mapping. LiDAR can produce accurate terrain maps even where forest cover gets in the way of traditional photography. The technique produces a very accurate Digital Elevation Model map (DEM). LiDAR is a useful topographic mapping tool for three reasons :
  - Accuracy
  - Productivity
  - Provides its own illumination.

These characteristics overcome the major liabilities of photogrammetry in forested terrain. The maps produced by LiDAR are very clear and detailed and in many cases reveal evidence of past landslides that are virtually invisible by other means due to heavy vegetation cover.

The use of GIS is extremely important in both investigating and helping to establish the spatial relationships between causative factors and landslide events, and also in preparing map products of susceptibility, hazard and risk. For the first purpose, the development of spatial relationships, the GIS acts as an integrating framework for the analysis. By providing a management system for the variety of input spatial datasets and the tools for investigating their interrelationships, the GIS can greatly improve the efficiency of such analysis.

Some of the techniques used to reduce landslide hazards are mentioned (**Table 7.3**). These may be used in a variety of combinations to help to solve both existing and potential landslide problems. The techniques are generally applicable to all types of surface ground failure, including flows, slides and falls. The effectiveness of each hazard reduction technique varies with time, place and persons involved in the planning and implementing of the programme for reducing the hazard. The control of the landslide hazard system is easier for new developments for new developments as vulnerability can be restricted.

Table 7.3 Techniques for Reducing Landslide Hazards (Kockelman, 1986)

Discouraging new developments in hazardous areas by:
Disclosing the hazard to real-estate buyers
Posting warnings of potential hazards
Adopting utility and public-facility service-area policies
Informing and educating the public
Making a public record of hazards
Removing or converting existing development through:
Acquiring or exchanging hazardous properties
Discontinuing nonconforming uses
Reconstructing damaged areas after landslides
Removing unsafe structures
Clearing and redeveloping blighted areas before landslides

Providing financial incentives or disincentives by:
Conditioning federal and state financial assistance
Clarifying the legal liability of property owners
Adopting lending policies that reflect risk of loss
Requiring insurance related to level of hazard
Providing tax credits or lower assessments to property owners
Regulating new development in hazardous areas by:
Enacting grading ordinances
Adopting hillside-development regulations
Amending land-use zoning districts and regulations
Enacting sanitary ordinances
Creating special hazard-reduction zones and regulations
Enacting subdivision ordinances
Placing moratoriums on rebuilding
Protecting existing development by:
Controlling landslides and slumps
Controlling mudflows and debris-flows
Controlling rock falls
Creating improvement districts that assess costs to beneficiaries
Operating monitoring, warning, and evacuating systems

Under the sequence of survey and survey methods (IRC:SP:48-1998), an important measure to be added before fixing final alignment of a hill road is landslide hazard mapping. Before the determination of the Final Centre line, it is necessary to know areas prone to landslide. For areas with existing landslides, hazard maps show the areal extent of threatening processes where landslide processes have occurred in the past, recent occurrences. Most importantly, it shows the likelihood in various areas that a landslide will occur in the future, which will help in preparing the alignment of a road to a great extent, in a way that we can avoid areas susceptible to land slips and prepare alternate routes of alignment.

Hazard maps contain detailed information on the types of landslides, extent of slope subject to failure, and probable maximum extent of ground movement. These maps can be used to predict the relative degree of hazard in a landslide area and we can therefore plan accordingly to the kind of remedial measures that can be undertaken in order to prevent the area from further damage. Areas may be ranked in a hierarchy such as low, moderate, and high hazard areas. This helps us importantly in demarking areas which can completely be closed for transportation use, areas which needs greater inspection, areas where alignment of roads is possible and also aids in following a certain structure/framework for planning according to their ranks of low, moderate and high danger areas. In terms of high and very high hazard ranking sites, the primary intention is to concentrate on exposure reduction and a mix of exposure and hazard reduction, with the latter approach generally being the more expensive.

For virgin areas, hazard maps show the locations of past and present landslides. With the use of a hazard map, the magnitude of the possible slide can be calculated. This helps in the process of planning how a possible landslide should be dealt with, for example, to access whether the benefits of a prevention method outweigh its costs.

Landslide hazard mapping may be produced by a 'direct' or an 'indirect' method. For direct mapping the study area is zoned according to the location and the density of recorded landslides, then extrapolating to slopes of the same type that have not failed[116]. The assumption is that future landslides are more likely to occur on slopes where conditions are the same as those in which sliding has occurred previously. The indirect mapping method relies on the evaluation of factors that are considered to be significant in the initiation of slope failure and aggregating these.

Landslides can occur at a road section where:

a. The upslope drainage or the associated road drainage is partially or fully blocked or has an inadequate design capacity; during rainstorms the road section will collect a large volume of surface runoff from uphill areas, which may discharge onto the downhill slope, and

b. The slope below the road onto which the surface water may overflow is a substandard man-made feature, or steep natural terrain of marginal stability, or ground susceptible to erosion or washout by concentrated surface water flow.

(Refer to IRC:SP:48-1998 for further guidance of drainage in highways).

Table 7.4 Location which can be Considered Critical with Regard to the Impact of Drainage on Stability of Highway Slopes

1.	A long and sloping road with adjacent large uphill slopes which can intercept and collect a large volume of surface run-off and discharge it onto the downhill slopes in the event that nearby catchpits, drainage channels or road drainage components are blocked during heavy rain.
2.	Road sections traversed by drainage culverts/pipes during large catchment areas uphill, the blockage of the nearby stormwater inlets could lead to severe flooding and adversely affect the stability of slopes in the adjacent area.
3.	Road sections affected by slopes below a catchwater which could be subject to overflowing due to blockage of the catchwater.e.g : by landslide debris.
4.	Sag points of roads susceptible to large runoff from adjacent road surfaces and slopes which could be discharged onto downhill slopes.
5.	Road bends supported by downhill slopes.
6.	Road sections with significant elevation and large cambering (e.g: greater than 5%) which may lead to overflowing onto the downhill slopes.

7.4 Techniques for Hazard Reduction on Existing Roads

The challenge with hazard reduction is in identifying locations that are of sufficiently high hazard ranking to warrant spending significant sums of money on engineering works[155]. The costs associated with installing remedial works over long lengths of road are difficult to justify in economic terms and may well be unaffordable. Moreover the environmental impact of such engineering work should not be underestimated, having a lasting visual impact at the least and potentially other more serious impacts. It is considered that such works should be limited to locations where their worth can be proven. Critical review of the alignment of culverts and other conduits close to the road should be carried out as part of any planned maintenance or construction activities (**Fig. 7.2**).

Achieving a reduction in the hazard will involve physical engineering works to change the nature of a slope or road to reduce the potential for either initiation and or the potential for a debris flow to reach the road once initiated. Debris flows are dynamic in nature and quite often originate some distance above the road; when they reach the road they are relatively fast-moving, high-energy flows. The energy of these systems is a significant factor in determining the nature of the engineering works that can be used to effectively reduce the hazard to the road and its user. Hence, there are three broad approaches to the selection of hazard reduction works:

- **Road Protection:** Accept that debris flows will occur and take measures to protect the road. Potential solutions include debris basins, lined debris channels, debris flow shelters, overshoots and barriers (including ditches, walls and fences).
- **Debris Flow Prevention:** Carry out engineering works to reduce the opportunity for a debris flow to occur.
- **Road Realignment:** Realign the road.

Road realignment is undertaken as route improvement activities in order to improve the road in terms of both alignment and junction layout, in particular to reduce accidents and to ensure compliance with current design standards[116]. In cases where the debris flow hazard ranking is high and other factors indicate that some degree of reconstruction is required, road realignment may be a viable option.

With regard to the chapter 5 IRC:SP:48-1998, the sequence of survey and survey methods should also include the study and analysis of historical background checks of the present landslide before undertaking the survey of the site.

During the preliminary stages of an investigation reference should be made to records of development in the area which may contain information on site formation, site investigation, well boring, piling, foundations and previous instability of slopes[48]. Records held by the office in the Public Works Department and by the consultant architect or engineer for both public and private developments, although records for old developments may be scanty or non-existent. Site investigation contractors may hold useful information. Hazard and risk assessments combine geology and history to determine which technologies best will respond to a landslide event or to reduce future hazards. **Fig. 7.3** provides options for the highway slope management.

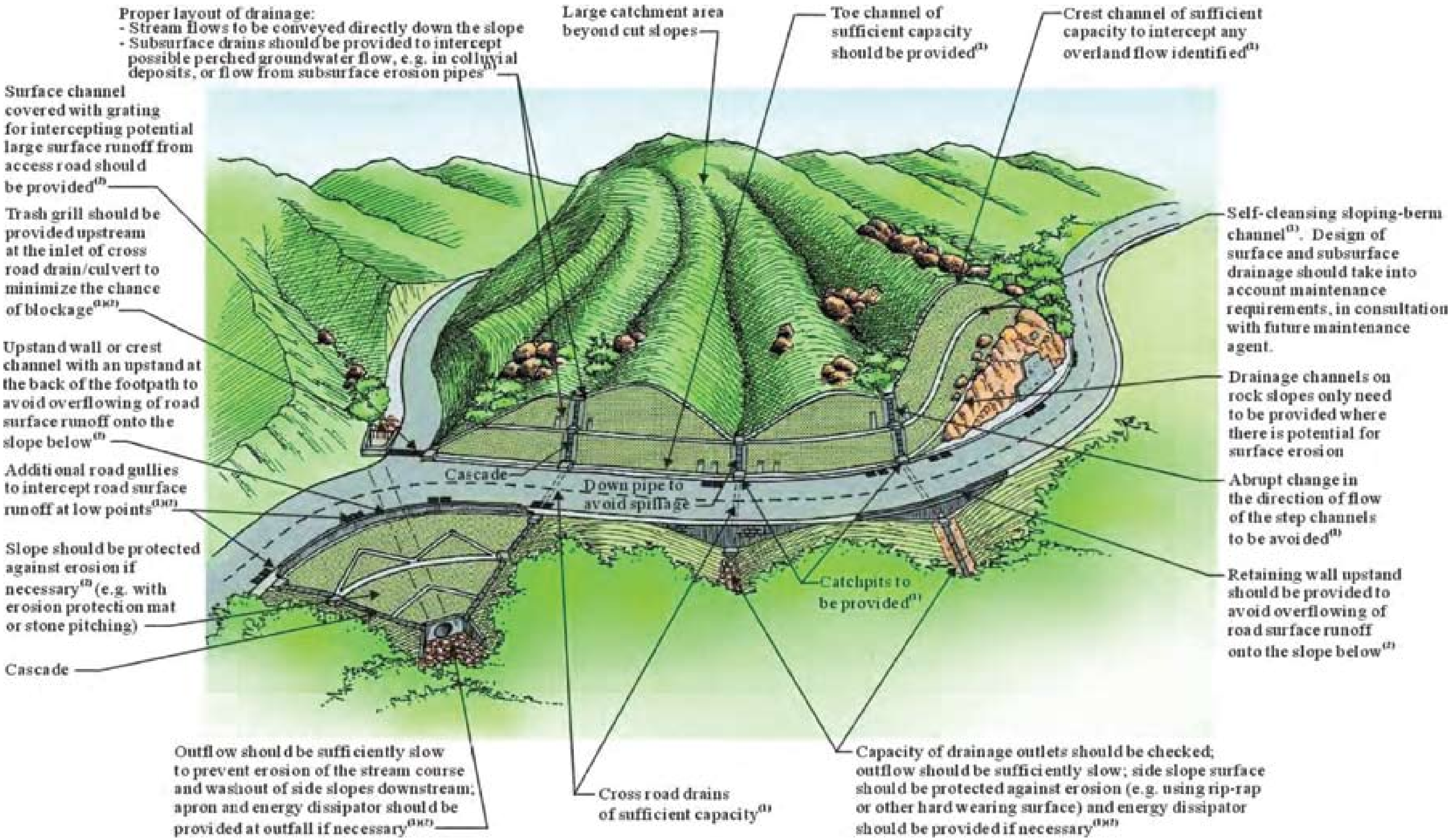


Fig. 7.2 Examples of Methods of Handling Surface Water at Critical Locations Along a Road

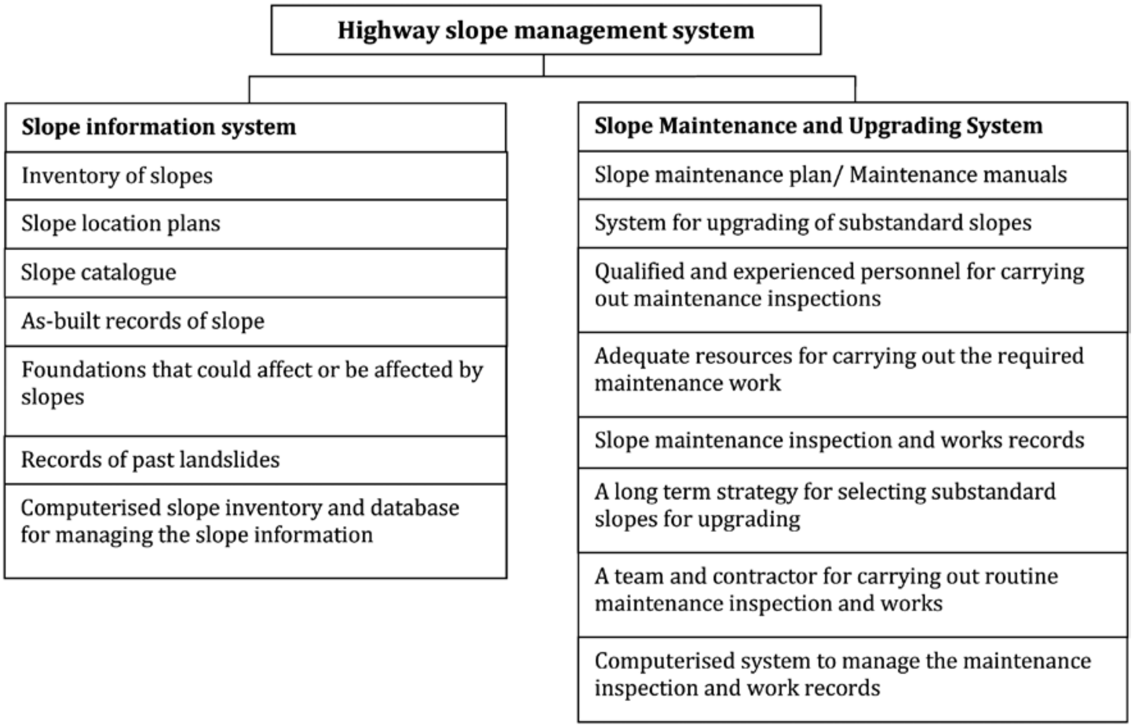


Fig. 7.3 Range of Options for Highway Slope Management System

7.5 Post Disaster Management of Landslide

The management and control of the adverse consequences of future landslide incidences will require coordinated, prompt, and effective response systems at the central and state government levels, and especially at the district and the community levels in the landslide affected areas[64]. Since many components of the response initiatives are the same for different types of disasters, systems need to be developed considering the multi-hazard scenario of various regions in order to optimally utilize the available resources.

Depending on the magnitude of the landslide and scale of the required response, the corresponding role players should be identified and mobilized at the district, state or national levels. The community in the affected neighborhood is always the first responder after any disaster. Trained and equipped teams consisting of local people should be set up in landslide prone areas to respond effectively in the event of a disaster. Rescue & relief operations shall be based on ground assessment of damage and losses. Preliminary assessment should be carried out immediately within 24 hours for planning the response. Teams should be constituted of officials drawn from various sectors to make assessment on the basis of on the spot visits, aerial surveys and information collected from primary and secondary sources. The Departments/Agencies of the State Governments responsible for various infrastructural facilities such as electricity, drinking water, telecommunication etc should repair the damage caused by the disaster and should take immediate steps to restore damaged essential services so that rescue & relief operations are conducted smoothly.

In the aftermath of disasters the affected people must be looked after for their safety, security and the well being and provided food, water, shelter, clothing, medical care etc. so as to ensure that the affected people live with dignity. The state governments should facilitate the involvement of the corporate and private sector and utilise their services and resources if offered to the government during the immediate post disaster situation. The India Disaster Resource Network (IDRN) should be maintained and updated regularly so that locally available resources are utilized effectively in the case of emergencies. The nodal agency and respective state governments should constitute multi-institutional and multi-disciplinary teams for carrying out post landslide field investigations to assess the hazard potential and estimate the risk involved. They will also document the lessons and disseminate the same to target audiences within the state and recommend cost effective practical measures. The nodal agency should oversee the progress of these efforts in a systematic manner.

For further details on post disaster management of landslide, refers to “National Disaster Management Guidelines-Management of Landslides and Snow Avalanches”, a publication by National Disaster Management Authority (NDMA). Apart from the administrative approach as given in the NDMA document; planning, inventorisation, deployment, use of equipment for mitigation, search & rescue, skill-set and training level of equipment operators, are also important aspects of post disaster management of landslide.

8 TECHNOLOGY FOR LANDSLIDE PREVENTION AND REMEDIATION

The key of successful landslide management strategy is to design workable and economically viable schemes of mitigation/preventive measures. The promotion of innovative and modern technologies based on proven workability becomes the unavoidable choice.

The thumb rule says that slope failure occurs due to imbalance in the driving and resisting forces of slope under the effect of gravitational forces. But the triggering factor/factors which cause such imbalance are different at different incidence of landslides, greatly depending upon the local conditions and hence this hazard is so varied in type and size. So it is essential to identify potentially hazardous slopes and control their instability by providing suitable remedial measures. For prevention and remediation of such consequences of landslides there are a number of effective remedial measures which can avoid or minimize their adverse effects. The slope can be stabilized by a single method or concomitant methods of prevention totally depending upon the nature, size, location, causative factors of the landslide. The effectiveness, acceptability and durability of remedial measures, to a large extent depend upon the quality of investigation carried out for identified correct problematic factors of the landslides.

8.1 Slope Instability and their Stabilization

Landforms are the products of the local balance between weathering, erosion and deposition and are continuously evolving. Slopes that are too steep for the weathered material to remain stable are subject to periodic failure. Instability may be associated with moderate to steeply sloping terrain or with land, which has been disturbed by man[35]. Natural slopes that have been stable for years may suddenly fail because of construction activities on hill slope and also other causes which are already mentioned in chapter 2.

8.1.1 *Appropriate Actions for Unstable Slope Treatment*

The detailed site inspection procedure as mentioned in Chapter 5: Investigation with or without ground investigations, reveals the nature of the problem that is faced, before the selection and design of suitable scheme of remedial measures. To control the slope instability problems, a general outline consisting of a decision-making process used for assistance in framing the problem and selection of the preferred remedial actions presented in **Fig. 8.1**. The recommended remedial measures/methods, as per Clause 6 of IS:14680:1999 can be followed for selection of various landslide control measures to avoid landslides in hill areas. These control measures are generally divided into four main practical groups as described in **Table 8.1**[134]:

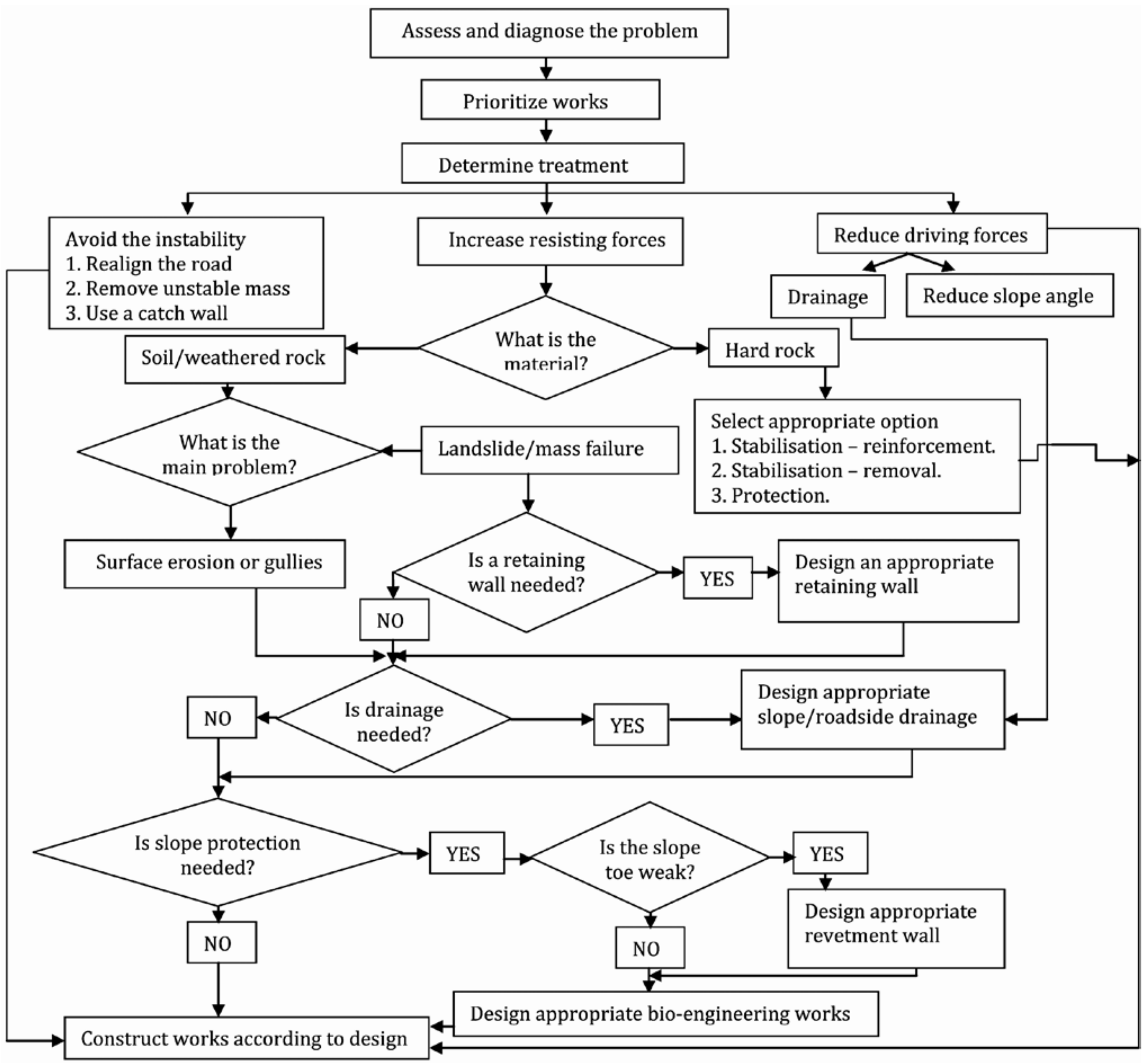


Fig. 8.1 Decision-Making Process for Selection of Remedial Measures
(Scott Wilson in Association with Lao Consulting Group)

Table 8.1 Brief List of Remedial Measures for Unstable Slope

1. Modification of Slope Geometry		**3. Retaining Structures**	
1.1	Removing material from the area driving the landslide (with possible substitution by lightweight fill)	3.1	Gravity retaining walls
1.2	Adding material to the area maintaining stability (counter weight berm or fill)	3.2	Crib-block walls
1.3	Reducing general slope angle	3.3	Gabion walls
2. Drainage		3.4	Passive piles, piers and caissons
2.1	Surface drains to divert water from flowing onto the slide area (collecting ditches and pipes)	3.5	Cast-in situ reinforced concrete walls
2.2	Shallow/deep trench drains filled with free draining geomaterials (coarse granular fills and geosynthetics)	3.6	Reinforced earth retaining structures with strip/sheet - polymer/metallic reinforcement element
2.3	Buttress counter forts of coarse-grained materials (hydrological effect)	3.7	Buttress counterforts of coarse-grained material (mechanical effect)
2.4	Vertical (small diameter) boreholes with pumping or self draining	3.8	Retention nets for rock slope faces
2.5	Vertical (large diameter) wells with gravity draining	3.9	Rockfall attenuation oxr stopping systems (rocktrap ditches, benches,fences and walls)
2.6	Sub-horizontal or sub-vertical boreholes	3.10	Protective rock/concrete blocks against erosion
2.7	Drainage tunnels, galleries or adits	**4. Internal Slope Reinforcement**	
2.8	Vacuum dewatering	4.1	Rock bolts
2.9	Drainage by siphoning	4.2	Micro piles
2.10	Electro-osmotic dewatering	4.3	Soil nailing
2.11	Vegetation planting (hydrological effect)	4.4	Anchors
		4.5	Grouting
		4.6	Stone/lime cement columns
		4.7	Heat treatment
		4.8	Freezing
		4.9	Electro osmotic anchors
		4.10	Vegetation planting (root strength mechanical effect)
Source :	Popescu, 2001, BIS 14680:1999, TRB: Special Report 247, BIS 14458 (Part 1):1998, BIS 14458 (Part 7):1998, BIS 14458 (Part 6):1998, BIS 14458 (Part 9):1998, IRC:SP:48-1998		

There are a number of levels of effectiveness and levels of acceptability that may be applied in the use of these measures, for while one slide may require an immediate and absolute long-term correction, another may only require minimal control for a short period[135]. Thus the mitigation measures chosen for a given slope must be analyzed recognizing that different mitigation measures require analyses for different methods of failure.

8.1.2 *Cost Implication of Treatment*

There are many alternatives (**Table 8.2**) to deal with the instability of slope such as avoid the instability, reduce driving forces, increase resisting forces by application of an external force, increase resisting forces by increasing internal strength, protect the surface etc[155]. Each alternative has many common techniques that should be recognize for resolving slope instability including consideration of what these techniques likely to cost as low or moderate or high.

Table 8.2 Various Remedial Techniques Against Cost Implication

Options	Implications
Avoid the instability	
Re-align road	High cost; may create similar problems; slow to implement.
Completely or partially remove unstable material	Low cost; only feasible for minor, shallow slips; may create further instability
Construct catch wall	Moderate cost: There must be enough space so that the wall is capable of containing slip debris and access for clearance; slip may become more extensive upslope.
Reduce driving forces	
Reduce slope angle	Low cost; unlikely to be feasible in steep terrain, cut surface will need erosion protection, right of way/sufficient space may not be available
Drain surface	Low cost; will only reduce surface infiltration, therefore combine with other techniques.
Drain sub-surface	Moderate cost; assumes that the water table is above the slip surface; more effective when sliding mass is relatively permeable.
Increase resisting forces by application of an external force	
Construct retaining wall	Moderate cost; must be founded below slip surface; may need to be combined with other techniques.
Construct toe berm	Low cost; usually requires significant space at toe.
Install anchors	High cost; specialist installation equipment needed, potential corrosion/ monitoring problems.
Increase resisting forces by increasing internal strength	
Drain sub-surface	Moderate cost; assumes that the water table is above the slip surface; more effective when sliding mass is relatively permeable.
Install soil nailing	High cost; specialist installation equipment needed.
Use bio-engineering	Low cost; not suitable for very steep slopes and deep-seated failures.
Protect the surface	
Construct revetment or rip-rap	Moderate cost.
Use bio-engineering	Low cost; not suitable for very steep slopes or hard, compacted soils.
River training works	Usually high cost, but only required in particular locations.

8.2 Stabilization Methods for Different Types of Slope Failure

8.2.1 *Rockfall Mitigation Measures*

8.2.1.1 Prevention measures

Measures (**Fig. 8.2**) are taken to increase the resisting forces or minimizing the disturbing forces causing the rockfall and prevent any detachment and movement of rocks. e.g. Nailing, Deep Anchoring, Correcting the rock slope by trimming and Benching, Reinforcing the slope face etc.

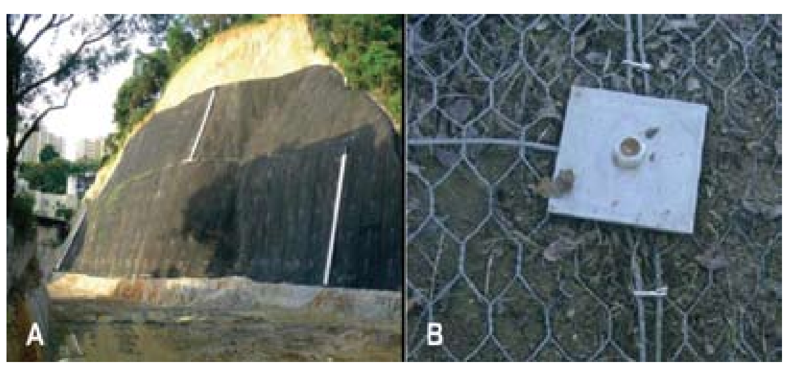


Fig. 8.2 (A) Soil Nailing & (B) Anchor and Steel Grid

8.2.1.2 Retention measures

The measures in this category will not totally nullify or prevent the detachment and tendency to move. Measures (**Fig. 8.3**) are taken to contain or retain the rock masses which are on the verge of movement. E.g. Mesh/ Net/Netting with nails or anchors surficial strengthening, shortcreting, Chemical stabilization of slope face etc.

Fig. 8.3 Surfacial

8.2.1.3 Protection Measures

These measures (**Fig. 8.4**) don't affect or prevent the process of rock detachment. They guide the falling rock and control the distance and direction in which the falling rock travels thus protecting the area prone to hazards. E.g. Drapery system with steel wire mesh and steel cable panels, Rockfall prevention barriers, Ditches, Rock sheds etc.

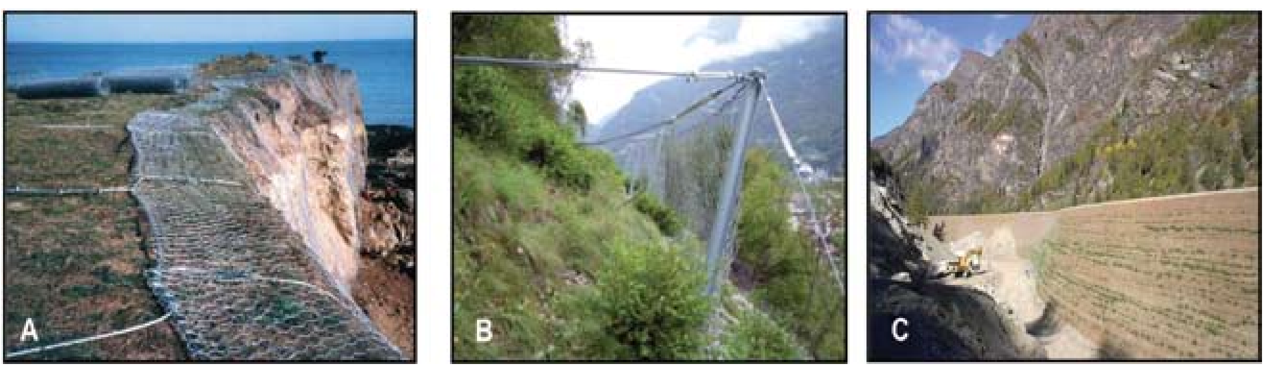


Fig. 8.4 A. Drapery System, B. Protection Barrier & C. Protection Embankment

8.2.1.4 Warning measures

These measures help the detection of an impending rockfall or slope movement and thereby provide sufficient time for taking precautionary measures to prevent any loss of life and property due to rockfalls.

8.2.2 *Rockfall Mitigation Systems In Practice*

8.2.2.1 Rockfall drapery systems (mesh/cable nets)

These systems are also used to control falling detached rock block from slopes and preventing the rock blocks from falling onto roads or areas, directly, where loss of life or property damage is possible. There are different types of rockfall drapery systems, as presented in **Table 8.3**, along with their purpose and limitation.

Table 8.3 Different Types of Rockfall Drapery Systems

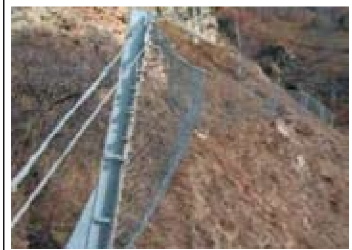
Types	Description /Purpose	Limitation	Figure
Draped Mesh/Nets	Hexagonal wire mesh, cable nets/ panels or high-tensile strength steel mesh of rhomboidal or hexagonal or circular in shape, draped over aslope face to slow erosion, control the decent of the falling rocks and restrict them to the catchment area.	Require a debris collection catchment area. Must consider debris and snow loads on anchors. Typically limited to areas with rocks smaller than 1.5 m (5 ft) in diameter. Visible to passing motorists.	
Anchored Mesh/Nets	Free-draining pinned/anchored in place nets or mesh. Used to apply active retention force to retain rocks and soil on a slope.	May from pockets of accumulated rock. Can be difficult to clean out. Can be visible to passing motorists.	

8.2.2.2 Rockfall barriers/fences

Rockfall barriers of variable geometry are made of a complex system of steel cable panels or ring net panels, a double-twist wire mesh layer for the containment of small rock fragments, steel cables connected to structural elements, posts, energy dissipater devices and anchors[148]. There are different types of rockfall barriers, as discussed in **Table 8.4**, along with their purpose and limitation.

Table 8.4 Different Types of Rockfall Barriers

Types	Description /Purpose	Limitation	Figure
Earthen Barriers	Barriers constructed of natural soil and rocks (berms) or mechanically stabilized earth (MSE), placed at the toe to improve its effectiveness. MSE walls in the particular, can withstand large kinetic energies and repeated impacts.	Catchment area must be periodically cleaned to remove accumulated material. Berms of considerable height require a wide base area.	
Flexible retaining walls	Flexible retaining barriers that provide protection from low energy impacts. Relatively cheap, easy to obtain and fast to install.	High stiffness causes barriers to cracks and or shatter in high-energy impact. Not visually appealing.	
Structural walls	Rigid barriers used to intercept falling rocks and restrict them to a prescribed catchment area. Facing can be installed on road side of walls to improve aesthetics.	Catchment area must be periodically cleaned to remove accumulated material. Prone to damage by high-energy events.	

Types	Description /Purpose	Limitation	Figure
Flexible Barriers	Flexible barriers made of wire ring or high strength wire mesh with high energy (upto Maximum-8500 kJ is available in market) –absorption capacity, supported by steel posts and anchor ropes with a deformable braking system (as per European Technical Approval Guidelines). Fence is fixed at the bottom to hold rocks.	Must be cleaned out periodically. Fairly expensive to construct and prone to damage by higher energy events. Do not blend well into surrounding landscape.	
Attenuators	Flexible barriers similar to fencing (above) but not attached at bottom (an extra length of fence lies on the slope face); allow rocks to move beneath the two sections of fence and direct them into a catchment area.	Visible to passing motorists. A catchment area is required and must be periodically cleaned.	

8.2.2.3 Benched slopes

Benches are flat catchment areas typically constructed at regular elevation intervals within rock cuts. Main purpose of these benches is to control the degradation of the slope and control rockfalls.

8.3 Landslide Protection Measures

8.3.1 *Retaining Structures*

There is already a wealth of information available on retaining structure, the following is the information found in different codes & practiced:

- In Clause 9.2 of Chapter 9: Structures and Protective works: IRC:SP:48-1998 and Chapter 14: Special requirement for Hill Roads: IRC:SP:73-2007.
- About its design criteria in Clause 7.3.2 of Chapter 7: Corrective measures and design considerations; State of the Art: Landslide Correction Techniques.
- Code of practice for different types of Retaining walls and their selection for stability of hill slopes are given in IS:14458 (Part 1:1998). Design of Retaining/ Breast walls are given in IS:14458 (Part 2:1997)(Reaffirmed 2007)
- Retaining Wall for Hill area- Guidelines; Construction of dry stone walls; IS:14458 (Part 3:1998) (Reaffirmed 2007).
- Design and construction of reinforced earth retaining walls: IS:1445 (Part 10:1998)
- Special Report No. 21: State of the Art: use of Jute Geotextiles in Road construction and prevention of Soil Erosion/Landslide.
- IRC:56-2011: Recommended practice for treatment of Embankment and roadside slopes for Erosion Control (First revision).

8.3.2 *Gabion Wall*

Gabion walls are made up of wire mesh crates filled with stones and erected as gravity retaining structures (**Fig. 8.5**) each unit is rectangular and is fabricated from mechanically woven, double twisted, hexagonal shaped mesh of soft annealed heavily zinc coated steel structure strengthened by mechanical selvedging the edges by high diameter wire. The following national and international references having detailed information about gabion walls have been collected and presented as follows:

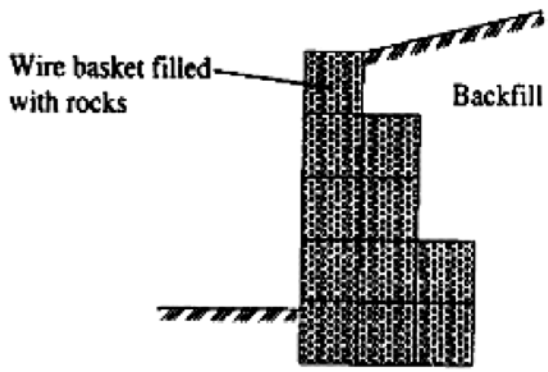


Fig. 8.5 Typical Gabion Wall

- IRC:SP:48 (Hill road manual) briefly describes the concept as sausage wall made by forming sausages of galvanized iron or steel work netting of 4 mm dia having 10cm square or hexagonal openings and filling the sausages with local hard boulders/stones and wrapping the wire net at the top. The manual highlights the advantages of flexibility and free drainage properties of gabion wall.
- BS:8002:1994: Code of practice for earth retaining structures.
- Standards IS:16014:2012, Mechanically woven, double twisted, hexagonal wire mesh gabions, revet mattresses and rock fall netting (galvanized steel wire or galvanized steel wire with PVC coating).
- Section 2500 of Specifications for Road and Bridge Works (Fifth Revision).
- EN 10223 Part 3 : Hexagonal steel wire netting for engineering purposes.
- ASTM A 974 - 97 : Standard specification for welded wire fabric gabions and gabion mattress.
- ASTM A 975 – 97 : Standard specification for Double – twisted Hexagonal mesh gabions and rivet mattress.

8.3.3 *Soil Nailing*

Soil nailing essentially involves reinforcing and strengthening of existing grounds by installing closely-spaced steel bars, called nails, into hill slope. A soil-nailed system can override local weaknesses in the ground through stress redistribution and is less vulnerable than unsupported cuts to undetected adverse ground and groundwater conditions that have not been accounted for in the slope stability analysis. **Fig. 8.6** shows the cross-section of a typical soil-nailed cut slope.

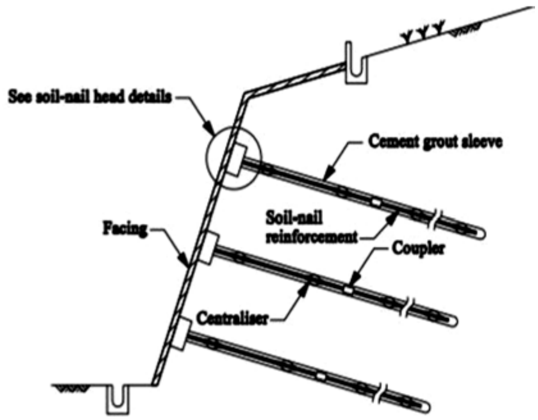


Fig. 8.6 Cross-Section of Soil-Nailed Cut Slope

Based on the project requirement, variety of facings may be adopted – viz. steel meshes and steel cable panels with high stiffness and low deformability which may be used in combination with erosion control mattresses, fibre reinforced shotcrete, etc.

There are following referred codes of practice and design manuals for design of soil nailing are:

- BS 8006-1:2010 Code of practice for strengthened/reinforced soils and other fills.
- BS 8006-2:2011-Code of practice for strengthened/reinforced soils. Soil nail design
- U.S. Department of Transportation, Federal Highway Administration (FHWA 1998), Manual for Design and Construction Monitoring of Soil Nail Walls.
- Geoguide 7 - Guide to soil nail design and construction, Geotechnical Engineering Office, Civil Engineering Department, The Government of the Hong Kong, 2008.

8.3.4 *Ground Anchor*

A pre-stressed grouted ground anchor is a structural element installed in soil or rock that is used to transmit an applied tensile load into the ground (**Fig. 8.7**). Key international documents as referenced related to ground anchors are as follows:

- BS EN 1537 2000: Execution of special geotechnical work on Ground Anchors.
- BS 8081 1989: Code of practice for ground anchorages. This comprehensive code covers the full range of design, materials, corrosion protection, execution, testing and maintenance aspects associated with ground anchors.
- FIP 1996: Design and construction of prestressed ground anchorages. They provide a guide to the planning, installation, testing and monitoring of permanent and temporary ground anchorages normally bonded to the ground by cement grout. The recommendations do not deal with the overall design of anchored structures or excavated faces.

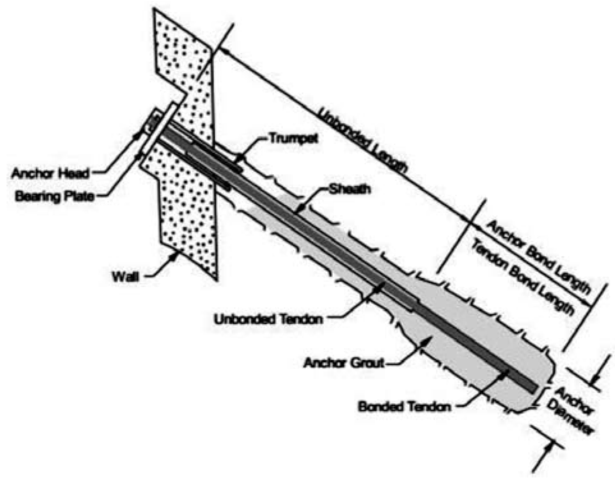


Fig. 8.7 Grouted Ground Anchor

8.3.5 *Drum Retaining Wall/Drum Anchored Diaphragm wall*

A simple method and low cost technology for construction of retaining wall to stabilize slopes has been developed by Bhandari (1987), which promotes extensive use of slope waste and landslide debris. The system of drum anchored diaphragm walling consists of empty bitumen drums interconnected vertically (**Fig. 8.8**) and laterally, filled up with wasteful debris to achieve gravitational effect and suitably anchored at the slope foundation as well as on to the slope retained. The system of retaining wall makes use of empty bitumen drums to serve as containers. This technology already implemented at Kaliasaur landslide on Rishikesh - Badrinath highway[19, 73 and 158] as mentioned in Bhandari (1987), IS 14680:1999 Landslide control - Guidelines, State of the Art report: Landslide Correction Techniques SOA(1995).

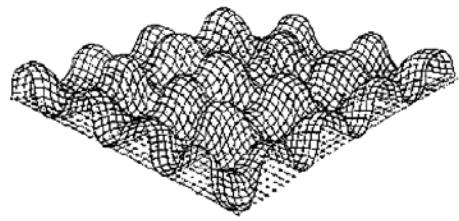
Fig. 8.8 Drum Anchored Diaphragm Wall

8.3.6 *Non-Biodegradable Systems*

8.3.6.1 Geosynthetic mat

Geosynthetic mats shall be three dimensional structures made of non-biodegradable materials like polypropylene, polyethylene, nylon or similar polymer fibers that are extruded or heat bonded at contact points to provide a dimensionally stable matrix to prevent soil erosion on slopes (**Table 8.6**).

Table 8.6 Geosynthetic Mats

Types	Figure
Consists of a flexible 3D polymer mat which initially stabilizes the surface whilst assisting vegetation to establish. It goes on to provide long-term, tenacious reinforcement of the root system. The mats have a flat, high tensile modulus base layer bonded to an upper cuspated surface which provides an array of pockets and traps for topsoil retention.	
3D permanent erosion control mats composed of UV stabilized non-degradable synthetic fibers. These can be integrated with steel mesh reinforces the geomat, significantly increasing the tensile strength of the mat, enhancing its erosion protection and shear resistance capacity when compared to un-reinforced erosion mats.	

8.3.6.2 Geogrid

Geogrids are now a day widely used for increasing slope stability and erosion control. (**Fig. 8.9**) can be an economical alternative to conventional slope design as mentioned in FHWA (1998)[173]. Soil reinforcement using high tensile strength inclusions can increase the shear resistance of a soil mass. It permits construction of soil structures at slope angles greater than the soil's angle of repose.

However, 3 dimensional erosion control mats are best suited for erosion control applications and where tensile strength and shear resistance is required there the steel wire mesh reinforced 3 dimensional mats are best utilized. This is because normal geogrids are not able to last long due to UV exposure. Also there is the danger of it being a fire hazard.

8.3.7 *Bioengineering Systems*

8.3.7.1 Coir geotextile

Coir Geotextile are permeable coir fabrics made from coir fiber extracted from coconut husk either by natural retting or by mechanical process. The open weave of Coir Geotextile are used for stabilization of soil through vegetation against erosion of landscape and soil slopes and acting as a ground cover or mulch.

The following Indian Standards has been published by Bureau of Indian Standards on the account of Coir Geotextile:

- IS:15869:2008 Textiles-Open Weave Coir Bhoovastra-Specifications.
- IS:15868: (Part 1 to 6): 2008 Natural Fibre Geo textiles (Jute Geo textiles and Coir Bhoovastra)-Method of Test.
- IS:15871:2009 Use of Coir Geo textiles (Coir Bhoovastra) in Unpaved Roads-Guidelines.

- IS:15872: Application of Coir Geotextiles (Coir Woven Bhoovastra) For Rain Water Erosion Control in Roads, Railway Embankments and Hill Slopes - Guidelines (2009).

The standard IS:15872:2009 prescribes the code for guidelines of woven coir bhoovastra suitable for application in slopes of road and railway embankments and also in hill slopes including the selection of woven coir bhoovastra and installation methods.

8.3.7.2 Jute geotextile

Jute is a natural fiber out of which Jute Geotextiles (JGT) can be made by the special treatment and weaving processes. Jute geotextile being a natural fabric is biodegradable and environment-friendly. It has good hygroscopic and hydrophilic properties. Jute geotextiles are most drapable among all types of geotextiles-Both natural and manmade. Properly designed Jute geotextiles lay on slopes or any other exposed soil surface provides a cover over exposed soil lessening the probability of soil detachment and at the same time reduces the velocity of surface run-off, the main agent of soil dissociation. IS:14986:2001 & SOA(2012) has covered the various aspects like specific requirements, selection, installation method, monitoring and requirement of packing related to geo textile.

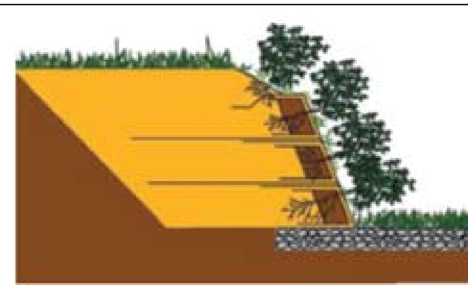
8.3.8 *Biotechnical Slope Protection*

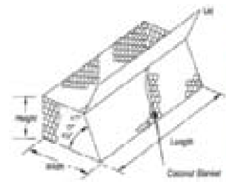
In Biotechnical Slope Protection, vegetation is used as surface protection and to augment the strength of soil in which it grows, usually combined with naturally occurring or recycled inert materials – timber, stone, iron and steel cables and meshes. These vegetated composite soil bodies or structures are 'soft' – flexible and multi-redundant statically and visually attractive.

Bioengineering is the use of vegetation, mostly shrubs and grasses, either alone or in conjunction with stone and concrete protection works such as retaining walls etc. to enhance the stability of slopes. Soil bioengineering combines mechanical, biological, and ecological concepts to prevent shallow slope failures and erosion. Basic approaches to upland slope protection and erosion control can be divided into two general categories:

- Living and
- Nonliving. Frequently, living and nonliving measures are combined to form a system (**Table 8.7**).

Table 8.7 Living and Nonliving Upland Slope Protection and Erosion Control Measures/Solutions

Soil Bioengineering Solutions	Figure
Reinforced Slope with green facia Unit- It is a reinforced soil system forming structures with 60 degree facings. The vegetation can be incorporated after installation of the structure. It is often installed with soil bioengineering techniques such as live staking and brush layering. For detailed specifications please refer Section 3105.1.5 of MORTH Section 3100.	

Elliptical Wire Basket filled with stone and soil mix- It is an elliptical basket made of steel wire mesh and lined with coconut fiber blanket. The blanket is used to contain a soil and stone mix. It can be used with geogrid to form a reinforced soil structure and are frequently vegetated with brush layering.	
Special sized gabions with green facia-These may be a trapezoidal gabion basket or a site specific solution (considering feasibility of manufacturing) made of steel wire mesh with an inclined front face suitable inclination and lined with coconut fiber blanket. They provide immediate erosion protection and create hospitable conditions for healthy plant development. They are filled with a mix of soil and stone to offer a substrate for insertion of cuttings, rooted woody plants and/or herbaceous plants.”	 

8.3.8.1 Greening techniques

Greening techniques for slope stabilization can be divided into three categories i.e. mulching system, planting long-rooting grass and fiber reinforced soil system. These techniques have their own unique characteristics[79]. They vary in applications, installation procedures, materials required and vegetation, etc. There characteristics and advantages are mentioned in **Table 8.8**.

Table 8.8 Characteristics and Advantages of Various Greening Techniques

Greening Techniques	Characteristics	Advantages
Mulching System	• Easy to apply for single layer, more complicated with multiplayer mat system • Relies on anchor pins for securing mat onto slope surface • Long-term maintenance on anchor pins • Not easily applicable on uneven surfaces • Cannot accommodate existing vegetation • Only grass can be grown on • Pockets of voids at interface are prone to fire hazard • Sustainability is questionable with limited space for root development	• Higher adhesive capacity on steep slope • Full vegetation on non-soil surface • High resistance to rain erosion • High water retaining capacity • Long-lasting fertilisers • High gas permeability • No bulge effect • Light in weight • Adaptable to rough surfaces
Planting Long-rooting Grass	• A shotcrete surface with drilled holes for planting the grass • Can be applied to uneven surfaces • A single type of long-rooted grass system is used • As the grass grows longer, it will cover the concrete exposed • This grass system does not blend into the existing environment • Cannot produce long-term ecological equilibrium	• Natural and environmentally friendly • Cost-effective • Fast and easy installation • Can be applied on steep slope • Low maintenance • High vegetation coverage • Seasonal greening • Non-invasive to other plant species

Greening Techniques	Characteristics	Advantages
Fiber Reinforced Soil System	● Easy to apply ● Easily applicable on uneven surfaces ● Can be easily accommodated with existing vegetation and environment ● Strengthening soil through a variety of flowers, trees, shrubs and grass grown ● Soil is reinforced and stable to reduce erosion ● Provides good nutrients for vegetation grown ● Develop a healthy root system and provide a natural ecosystem	● Self-sustained vegetation system with low maintenance ● Fibre strengthens soil particles to prevent erosion ● Visual improvement of the slope with various plant species ● Restoration of natural habitats on the slope

8.4 Debris Flow Protection Measures

8.4.1 *Flexible Ring Net Barriers*

A new type of debris flow mitigation measure, flexible ring-net barrier systems, are cost-effective and efficient compared to massive concrete barriers. It can ideally be used to span the cross section of a river bed or drainage on hill slope (**Fig. 8.10**) to stop the expected debris flow volume and to drain the material. There are two different set-ups of the barriers (**Fig. 8.11**).

- **Open slope barriers:** For wide U-shaped channel cross sections
- **Channel barriers:** For narrower V-shaped channels cross sections

In both systems, a wire ring-net is mounted between the horizontal steel wire ropes that are anchored in both sides of the channel side or open slopes. Based on different slope/channel configurations, variety of different geometries may be adopted as shown in figures below.

Fig. 8.10 Flexible Ring Net Barriers on Hill Slope

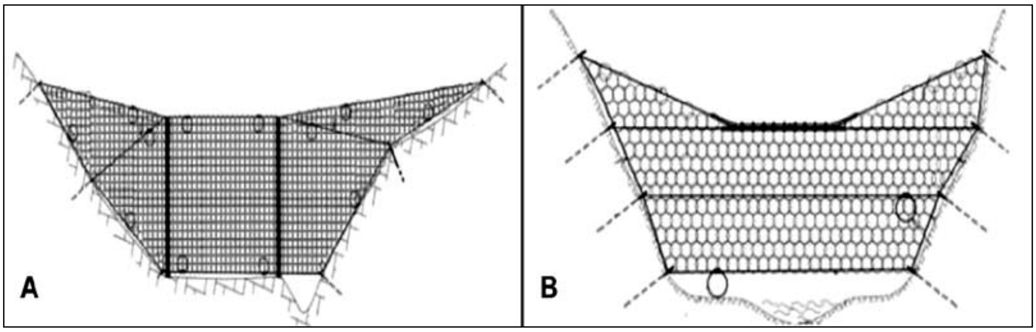


Fig. 8.11 Flexible Ring Net Barriers A. U-Barrier System and B. V-Barrier System

8.4.2 *Check Dams*

These are small barriers or dams constructed across natural or man made drainages, or other channelized flow of water. A properly designed, constructed, and maintained check dam will reduce channel erosion by reducing flow velocity and encouraging sediment settlement. A check dam either filters the water for sediment as it passes through the dam or retains the water, allowing the sediment to settle while the water flows over the dam (**Fig. 8.12**).

Fig. 8.12 Check Dam Placed Across Natural Drianage

8.5 Drainage and Surface Protection

The following techniques may be considered to limit the destabilizing effects of rising groundwater due to development:

- ✓ **Surface water drains (table drains) -** are often used to prevent scour and limit inflow to a slope. Other than in rock, they are relatively ineffective unless they have an impermeable lining. They should be cleared regularly and as required.
- ✓ **Surface Protection –** gabions and mattresses can be provided for surface protection, it is possible to construct flexible structures that effectively sustain eroding slope and also preserve their natural look thus providing eco-compatible solutions.
- ✓ **Sub-soil drains-** are often constructed behind retaining walls and on hillsides to intercept groundwater. They should be laid in a sand/gravel, bed and protected with a graded stone/geotextile filter to reduce the chances of clogging. These drains should always be laid to a fall of at least 1 vertical on 100 horizontal.
- ✓ **Deep, underground drains-** are usually used only in extreme conditions, where the landslide risk is assessed as not being tolerable and other stabilization measures are considered to be impractical. They work by permanently lowering the water table in a slope. Both an increase and a reduction in the normal flow from deep drains could indicate a problem if it appears to be unrelated to recent rainfall.

9 REFERENCES

1. Arnhardt, C., Asch, K., Azzam, R, Bill, R., Fernandez-Steeger, T.M., Homfeld, S.D., Kallash, A., Niemeyer, F, Ritter, H., Toloczyki, M., and Walter, K. 2007. Sensor based Landslide Early Warning System - SLEWS. Development of a geoservice infrastructure as basis for early warning systems for landslides by integration of real-time sensors. GEOTECHNOLOGIEN Science Report. Early Warning Systems in Earth Management. Kick-Off-Meeting 10 October 2007 Technical University Karlsruhe, pp.75 - 88.

2. Arora. K., Anbalagan. R., A Report on Overview of Landslide Hazard and Risk Practices in India; Department of Civil Engineering and Earth Sciences.

3. APEGBC, 2010. Guidelines for Legislated Landslide Assessments for Proposed Residential Developments in BC, Association of Professional Engineers and Geoscientists of British Columbia.

4. Appendix B. Introduction to Landslide Evaluation Tools - Mapping, Remote Sensing, and Monitoring of Landslides, The Landslide Handbook A Guide to Understanding Landslides.

5. ASCE Los Angeles Section Geotechnical Group, 2002. Recommended Procedures for Implementation of DMG Special Publication 117 Guidelines for Analyzing and Mitigating Landslide Hazards in California. A publication of the Southern California Earthquake Center. 132 p.

6. ASTM D4750-87(2001) Standard Test Method for Determining Subsurface Liquid Levels in a Borehole or Monitoring Well (Observation Well).

7. ASTM A 974 - 97 : Standard specification for welded wire fabric gabions and gabion mattress.

8. ASTM A 975 – 97 : Standard specification for Double – twisted Hexagonal mesh gabions and rivet mattress.

9. AUSTRALIAN GEOGUIDE LR6 (RETAINING WALLS), Australian Geomechanics Vol. 42 No. 1 March 2007.

   (http://lrm.australiangeomechanics.org/wpcontent/uploads/2012/04/Geog_LR06_Retaining1.pdf

10. Bhandari, R.K., Malhotra, B.R. and Natarajan, T.K. (1975): “A Composite Device to measure Differential Settlement, Tilt and Crack width in Building”. Ind. Geotech. Journal, 5:280-283.

11. Bhandari, R.K. and Sharma , S.C. (1975): “Mechanics and Control of Rockfalls”. Journal of the Institution of Engineers, India 57:14-23.

12. Bhandari, R.K. (1976): “Slip Surfaces - Their Properties, Determination and Importance”. Journal of Engg. Geology, 8:1:55-71.

13. Bhandari, R.K. (1978): “Geological Information: A Key to Control of Landslides in Shaly Formations”. Special Number of the Indian Science Congress.

14. Bhadnari, R.K., Malhotra, B.R. & Natarajan, T.K. (1980): “Instrumentation of the Ridge Slope at Simla, Proc. Int. Symp. On Landslides, New Delhi, 1:371-474.

15. Bhandari, R.K. and Sreenivasulu, V. (1980): “Some New Instruments for Landslide Studies”. Proc. Int. Symp. On Landslides, New Delhi, 1:343-348.

16. Bhandari, R.K. (1984): “State-of-the-Art-Report on Simple and Economical Instrumentation and Working Systems for Landslides and other Mass Movements”. Proc. Fourth Inst. Symp. Landslides, Toronto, 251-273.

17. Bhandari, R.K., Mehrotra, G.S., Nanwal, Kumar Kishor (1985). Hill Roads and Himalayan Landslides. Presented in a seminar on construction of Roads in Hill Areas, Nainital, July 7-9, 1985.

18. Bhandari R.K. 1987. Slope Instability in the Fragile Himalaya & Strategy for development. 19th Annual lecture, Indian Geotech. Journal, pp. 1-87.

19. Bhandari, R.K., 1994. Landslide Hazard Mapping in Sri Lanka - a Holistic Approach. Proceeding of National Symposium on Landslides in Sri Lanka, PP: 271- 284.

20. Bhandari R.K. and Kishor Kumar (2000). Malpa Rock Avalanche of 18 August 1998. Landslide News. International Newsletter, No.13, ISSN 0919 –5629.

21. Bobrowsky, P.T. (2005). Geoenvironmental Mapping: Methods, Theory and Practice. Published by Taylor and Francis.

22. British standard BS 8006-1: 2010, Code of Practice for strengthened/Reinforced Soils and Other fills.

23. BS 8002:1994: Code of Practice for Earth Retaining Structures.

24. BS EN 1537 2000: Execution of Special Geotechnical Work on Ground Anchors.

25. BS 8081 1989: Code of Practice for Ground Anchorages.

26. BS 8006-2:2011-Code of Practice for Strengthened/Reinforced Soils. Soil Nail Design.

27. Busslinger. M. April 2009: Landslide time-Forecast methods – A Literature Review Towards Reliable Prediction of Time to Failure., HSR University of Applied Sciences, Rapperswil, Switzerland.

28. Cawood. T et al., 2006- Survey and Geotechnical Slope Monitoring Considerations; The Journal of The South African Institute of Mining and Metallurgy; Vol. 106.

29. Climate Change, Impacts and Adaptation Strategies in the Alpine Space (ClimChAlp); Slope Monitoring Methods A State-of-the-Art-Report, Work package 6; Munich 2008.(Available through the website www.climchalp.org).

30. Corangamite Catchment Management Authority Training Manual 2008-2012.

31. Cruden, D.M., 1993, The Multilingual Landslide Glossary: Richmond, British Columbia, Bitech Publishers, for the IUGS Working Party on World Landslide Inventory in 1993.

32. Commentary on Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning" Ref: AGS (2007b).

33. D4.4 Rev. No: 2 Guidelines for the Selection of Appropriate Remote Sensing Technologies for Monitoring Different Types of Landslides. 2011.

34. EIA Guideline for Construction on Hillslopes, Sabah, Malaysia, Published by The Environmental Conservation Department, Sabah, Malaysia.

35. Encardio-Rite ANN-3002., 2003; Landslides and Role of Instrumentation in Mitigation of their Effect.

36. EN 10223 Part 3 : Hexagonal Steel Wire Netting for Engineering Purposes.

37. Fernandez et al 1999, Verification of Landslide Susceptibility Mapping: A Case Study, Earth Surf. Process. Landforms 24, 537-544 (1999).

38. FHWA (1998), Geosynthethic Design and Construction Guildelines, Publication no. FHWA HI-95-038, US Department of Transportation, Revised April 1998.

39. FIP 1996: Design and Construction of Pre-stressed Ground Anchorages.

40. Fleming, R.W., Johnson, R.B., and Schuster, R.L., 1988, The Reactivation of the Manti Landslide, Chap. A of The Manti, Utah landslide: U.S. Geological Survey Professional Paper 1311, p. 1–22, 1 pl.

41. EO Information Note01/2012: Surface Protection and Appearance of Slopes http://www.cedd.gov.hk/eng/publications/information_notes/doc/IN_2012_01E.pdf.

42. EO Information Note08/2012: Soil Bioengineering Measures for Natural Terrai Landslide Scars.

43. Gangopadhyay S. and Kumar Kishor (2009). "A Cover Article on Theme "Safety and Efficient Management of Road Network in Landslide Prone Areas". Journal of Science and Culture. India Science News association Kolkata, Vol.75 No.11-12, pp 380-388.

44. Gangopadhyay S. and Kumar Kishor (2012), "Hill Roads and Highways vs. Landslide Hazards", Seminar on Recent Trends in Highways Development, IRC New Delhi 10-11Oct, 2012, pp 155-165.

45. Gangopadhyay S., Kumar Kishor and Mathur Sudhir (2012), "Management of Indian Disaster on Indian Highways – A Critical Focus Area of R&D", Souvenir Diamond Jubilee of CSIR-CRRI, New Delhi, July 16, pp 53-57.

46. Geoguide 7 - Guide to Soil Nail Design and Construction, Geotechnical Engineering Office, Civil Engineering Department, The Government of the Hong Kong, 2008.

47. Geotechnical Engineering Office (GEO), 2000. Geotechnical Manual for Slopes (2nd Edition, 4th reprint). Government of Hong Kong publication. 300 p.

48. Grasso. V.F., 2009: Early Warning Systems: State of the Art and Future directions. UNEP Draft Report. Galeano. R., Katherine., Pedraza., L. F., Guevara. J. C; 2011; Design and Implementation of an Early Warning System Landslide Area for Bella Flor in the Framework of the Community Wireless Network in Ciudad Bolivar; World Academy of Science, Engineering and Technology 59.

49. Guidelines for Assessing Planning Policy and Consent Requirements for Landslide Prone Land, New Zealand.

50. "Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning" Ref: AGS (2007a).

51. Guidelines for Landslide Susceptibility, Hazard and Risk Zoning for Land-Use Planning, Engineering Geology.

52. Guidelines Risk Analysis – a Basis for Disaster Risk Management.

53. Guideline for European Technical Approval ETAG 027 of Falling Rock fall Protection Kits.

54. Highland, L.M. and Bobrowsky, P.T. 2008. The Landslide Handbook – A Guide to Understanding Landslides. USGS Circular 1325.

55. Highway Slope Manual, 2nd Draft, Govt of Hong Kong.

56. H. Marui, 1988, "Fao Watershed Management Field Manual: Landslide Prevention Measures", Food & Agriculture Org. of the United Nations, Rome.

57. 43 Hsai-Yang Fang, 1991, "Foundation Engineering Handbook" Springer, 923 pages.

58. Hylland, M.D. (editor), 1996. Guidelines for Evaluating Landslide Hazards in Utah. Utah Geological Survey Circular 92. 16 p.

59. Innovative Instrumentations for Landslide and Debris Flow Monitoring;Taiwan Water & Soil Instrumentation, Inc. www.hycom.com.

60. Intrieri. E., Nadim, F; Guidelines for the Design and Implementation of Landslide Early Warning Systems.

61. IRC:SP:48-1998 Hill Road Manual, The Indian Roads Congress 1998.

62. IRC:SP:19-2001 Manual for Survey, Investigation and Preparation of Road Projects Indian Roads Congress 2001.

63. India, 2009. National Disaster Management Guidelines - Management of Landslides and Snow Avalanches, a publication of the National Disaster Management Authority, Government of India.

64. IRC:75-1979," Guidelines for the Design of High Embankments," The Indian Roads Congress New Delhi, 1979.

65. IRC:SP:73 - 2007 Manual of Standards and Specification for Two Laning of State Highways on BOT Basis.

66. IRC:56-2011: Recommended Practice for Treatment of Embankment and Roadside Slopes for Erosion Control (First revision).

67. IS:14986:2001: Guidelines for Application of Jute geo-Textile for Rain Water Erosion Control in Road and Railway Embankment and Hill Slopes.

68. 55 IS:15869:2008 Textiles-Open Weave Coir Bhoovastra-Specifications.

69. IS:15868 (Part 1 to 6): 2008 Natural Fibre Geo textiles (Jute Geo textiles and Coir Bhoovastra)-Method of Test.

70. IS:15871:2009 Use of Coir Geo Textiles (Coir Bhoovastra) in Unpaved Roads-Guidelines.

71. IS:15872: Application of Coir Geotextiles (Coir Woven Bhoovastra) For Rain Water Erosion Control in Roads, Railway Embankments and Hill Slopes - Guidelines (2009).

72. IS:14680:1999 Landslide Control – Guidelines (Reaffirm date: January 2010).

73. IS:14458 (Part 1):1998 Retaining Wall for Hill Area - Guidelines: Part 1 Selection of type of wall (Reaffirm date: September 2010).

74. IS:14458 (Part 2):1997 Retaining Wall for Hill Area - Guidelines: Part 2 Design of Retaining/Breast Walls (Reaffirm date: September 2010).

75. IS:14458(Part 3):1998 Retaining wall for hill area - Guidelines: Part 3 Construction of Dry Stone Walls (Reaffirm date: September 2010).

76. IS:16014:2012, Mechanically Woven, Double Twisted, Hexagonal Wire Mesh Gabions, Revet Mattresses And Rock Fall Netting (Galvanized Steel Wire Or Galvanized Steel Wire With PVC Coating).

77. Jongmans. D., Garambois. S., 2007- Geophysical Investigation of “Bulletin Société Géologique de France 178, 2; 101-112” DOI : 10.2113/gssgfbull.178.2.101.

78. Juhani Aleksi HORELLI Thesis on Landslides in Hong Kong 2005, Department of Economics and Management.

79. Kane. F.W., Beck. J. T- Instrumentation Practice for Slope Monitoring.

80. Krauter. E- New methods of investigation and controlling of landslides; http://www.geo-international.info/Vortrage/newmethods.pdf

81. Kumar Kishor, Jangpangi Lalita and Gangopadhyay S. (2014), Highways vs. Landslides and their Consequences in Himalaya, Proceedings of World Landslide Forum 3, 2-6 June 2014, Beijing.

82. Kumar Kishor, Prasad P.S., Kathait Anil, Negi Indervir (2014), Monitoring of Critical Landslides and Design of Preventive Measures, Proceedings of World Landslide Forum 3, 2-6 June 2014, Beijing.

83. Kumar Kishor, Prasad P.S., Kathait Anil and Singh Indervir (2013), “Over Eight Decades Old “Young” Landslide – A Case Study”, Seventh international conference on Case Histories in Geotechnical Engineering, April 29 – May 4, 2013, Chicago.

84. Kumar Kishor, Prasad P.S., Goyal Nitesh, Kathiat Anil, Negi Indervir S. (2013), Successful Case Studies of Some Critical Landslides on Various Border Roads, Technical Seminar on “Construction of Roads and Bridges in Challenging Conditions like Hills, High Rainfall and Snow Bound Areas” July 18-19 2013, Pune.

85. Kumar Kishor, Devrani Rahul, Kathait Anil and Aggarwal Neha (2012), Micro-hazard evaluation and Validation of Landslide in a Part of North Western Garhwal lesser Himalaya, India. International Journal of Geomatics and Geosciences. Volume 2, No 3, P. 888-901 (Impact factor-3.00).

86. Kumar Kishor, Prasad P.S., Kathait Anil, Negi Inder Singh and Mathur Sudhir (2012), “Road Tunnel, A Need For Immediate Consideration To Avoid Loss And Sufferings From Landslide Disasters On Himalayan Highways”, WTC2012 - Tunneling and Underground Space for a Global Society, 18-23 May, Bangkok, Thailand.

87. Kumar Kishor, Kathiat Anil, Prassad P.S. (2012), “Strategies for Landslide Risk Mitigation on Indian Highways”, Proc. of the Indian geotechnical conference (IGC), December 13-15 2012, Delhi.

88. Kumar Kishor, Prasad P. Subramanya and Mathur Sudhir (2011). Debris Flows in North Eastern Region of India – a Case Study, 14th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, Hong Kong 23rd to 27th May.

89. Kumar Kishor, Prassad P.S, Kathiat Anil, Kalota Deera, Negi Indervir S., Kimothi, Shivashish & Mathur Sudhir, (2011), Landslide Susceptibility Analysis by Using Frequency Ratio Method of Patalganga Valley, Garhwal Himalaya, Proc. Landslide Hazard - Consequences and Challenges, CSIR-CBRI, Roorkee, Feb. 10-12, pp. 30-47.

90. Kumar Kishor, Prasad P.S., Kimothi Shivashish, Negi Indervir S., Kathait Anil, Dash Abhilipsa & Mathur Sudhir, (2011), Kinematic Slope Stability Analysis of Kaliasaur Landslide on NH-58, Garhwal Himalaya, Third Indian Rock Conference: INDOROCK-2011, Indian Society for Rock Mechanics and Tunneling Technology, Roorkee Chapter, Roorkee, October 13-15, pp. 341-350.

91. Kumar Kishor, Prassad P.S, Kathait Anil, Negi Indervir S., Dash Abhilipsa & Mathur Sudhir, (2011), Monitoring of Slope Behavior Through Simple and Cost-effective Instrumentation, Third Indian Rock Conference: INDOROCK-2011, Indian Society for Rock Mechanics and Tunneling Technology, Roorkee Chapter, Roorkee, October 13-15, pp. 429-434.

92. Kumar, K., Prasad, P.S., Mathur, S., Kimothi, S. (2010), Rockfall and Subsidence on Mumbai – Pune Expressway. International Journal of Geo-engineering Case Histories, Vol. 2, Issue 1, pp. 24-38.

93. Kumar Kishor, Devrani Rahul, Sudhir Mathur (2010). Landslide Hazard Potential Analysis Using GIS, Patalganga Valley, Garhwal, Western Himalayan Region of India, European Journal of Scientific Research, Vol.45 No.3, pp.346-366. (Impact factor: 0.047).

94. Kumar Kishor, Kimothi Shivashish, Prasad P.S., Singh Kanwar and Mathur Sudhir (2010), Landslide Hazard Potential Analysis of Patalganga Valley, Garhwal, Western Himalayan Region of India. 13th Annual International Conference and Exhibition on Geo-spatial Information Technology and Applications (Map India), Gurgaon, Jan 19th-21st.

95. Kumar Kishor, Jangpangi Lalita and Mathur Sudhir (2009) "Prominence & State of the Landslide Hazard Database and Inventory along Highways in Uttarakhand Himalaya" Geomatics 2009, National Conference,on Geomatics and Impact of Climate Change with Specific Reference to Mountain Ecosystem 4-6th February, Dehradun.

96. Kumar Kishor, Gupta Pankaj, Parsad P S and Mathur Sudhir, (2008) 'Design of Suitable Corrective Measures for Stability of a Critical Slope near Koldam, HP – A Case Study', Journal of Indian Highways, Indian Roads Congress, Vol. 36, No. 1, pp. 41-47.

97. Kumar Kishor, Prasad P.S., Goyal Nitesh & Mathur Sudhir (2007). Large – Scale-Mapping and Monitoring of the Patalganga Landslide", Disaster & Development, Journal of the National Institute of Disaster Management, Vol. 1, No. 2, pp. 187-196.

98. Kumar Kishor, Prasad P.S. and Goyal Nitesh (2007). Study of Rockfall on Mumbai-Pune Expressway - A Case Study. Journal of Rock Mechanics and Tunneling Technology, Vol. 13, No.2, pp. 129-139.

99. Kumar Kishor & Sati D. Exploring the History of Alaknanda - Patalganga Tragedy of 1970 & Possibility of its Recurrence and Impacts on Patalganga Basin - A GIS and Remote Sensing Based Study. Map India & Geomatics 2005, New Delhi, 7-9 Feb.' 05.

100. Kumar Kishor, Gupta Pankaj and Sikdar P.K. (2004). Devastating Events of Cloudbursts Leading Landslide Disaster and its Consequences in Garhwal Himalaya. Proceedings of the World Congress on Natural Disaster Mitigation, Vol. 2, 14-21 February, 2004, New Delhi.

101. Kumar Kishor, Panigrahi R.K., Mathur Sudhir and Sikdar P.K. (2003). A Case Study on Filed Investigation and Instrumented Monitoring of Powari Landslide, Himacahal Pradesh National Seminar on Disaster Management with Specific Reference to Landslides and Avalanches organized by BRO, October 2003, New Delhi.

102. Kumar Kishor, Gupta Pankaj, Yadav O.P. and Bandara R.M.S. (2000). Comparative Landslide Hazard Zonation Study in Garhwal Himalaya-A Case Study. Presented in the Silver Jubilee National Seminar on Geodynamics and Environmental Management of Himalaya - Dec. 4-7, 2000.

103. Kumar Kishor and Panigrahi R.K. (1999). Role of Geological Discontinuities in Slope Failure- A Case Study. Proc. Of International conference on Rock Engineering for Site Characterization to be held at Bangalore, 6-8 Dec., 1999.

104. Kumar Kishor, Tolia D.S., Kumar Satish (1997). Role of Vegetation in Mitigating the Effects of Masswasting. Journal of Indian Building Congress, New Delhi, Feb.1997, No.1, Vol. 4.

105. Kumar Kishor, Tolia D.S., Kumar Satish (1996) Landslide Hazard Evaluation in a part of Himalaya. Proc. of Seventh International Symposium on Landslides, Trondhiem, Norway, 17-22 June 1996.

106. Kumar Kishor, Tolia D.S., Kumar Satish (1996). Progressive (Compound) Landslides and Their Identification in the field. Proceeds of Indian Geo-technical Congress, Madras, 1996.

107. Landslide Hazard and Risk, edited by Thomas Glade, Malcolm G. Anderson, Michael J. Crozier.

108. Landslide in Ireland, Geological Survey of Ireland, Irish Landslide working group, 2006.

109. Landslide Hazard Rating Matrix and Database, Dr. Robert Liang University of Akron.

110. Landslide Loss Reduction: A Guide for State and Local Government Planning

111. Landslides in Hong Kong, Juhani Aleksi HORELLI University of Helsinki.

112. Landslide Hazard Zonation: a Review of Principles and Practice.

113. Landslide Risk Management Concepts and Guidelines, Australian Geomechanics Society.

114. Landslide Susceptibility Maps for the Kingston Metropolitan Area, Jamaica with Notes on their Use, UDS Publication No. 5, 1999.

115. Lawrence. J.C., Cook R.J; "A strategy for slope hazard assessment in road planning and maintenance; World Road Association; (PIARC 2003).

116. Leon, J., Bogardi, J, 2006., Dannenmann, S., Basher, R : (UNU-EHS), Bonn: Platform for the Promotion of Early Warning (UN/ISDR), Bonn.

117. Landslides in Japan, the Japan Landslide Society. http://www.tuat.ac.jp/~sabo/lj/ljap3.htm.

118. Ledesma. A., Hurlimann. M., Prat. P., Scavia. C., Amatruda. G., Poiser. R., Roth. W., Preh. A; D8. Guidelines on the Use of Numerical Methods for the Prediction of Failure; IMIRILAND; Impact of Large Landslides in the Mountain Environment; Identification and Mitigation o Risk.

119. Matternicht et al., 2005 Remote Sensing of Landslides: An Analysis of The Potential Contribution to Geo-Spatial Systems for Hazard Assessment in Mountainous Environments; Remote Sensing of Environment 98 (2005) pp. 284 – 303.

120. Machan George and. Bennett Victoria G (2008), "Use of Inclinometers for Geotechnical Instrumentation on Transportation Projects". Transportation Research Circular EBC129.

121. Matthias Busslinger, 2009. Landslide Time-Forecast Methods, A Literature Review Towards Reliable Prediction of time to failure. HSR University of Applied Sciences Institute für Bau and Umwelt Rapperswil, Switzerland.

122. Michoud C., Bazin S., Blikra L.H., Derron M.-H., and Jaboyedoff M., 2012 : Overview of Existing Landslide Early-Warning Systems in Operation, Institute of Geomatics and Risk Analysis, University of Lausanne, Switzerland.

123. Montana Geotechnical Manual, 2008; Instrumentation.

124. Morgan, R.P.C. and Rickson, R.J. (Editors) (1995). Slope Stabilization and Erosion Control: A Bio-engineering Approach. London, U.K., E. and F.N. Spon., 274p.

125. Murugesan, J, January 2009., Early Warning Systems for GLOFs and other mountain hazards, Climate Risk Management Team, Asian Disaster Preparedness Center, Paro, Bhutan.

126. National Landslide Hazards Strategy, A Framework for Loss Reduction, U.S. Geological Survey.

127. Ortigao JAR; Sayao ASEJ (eds.), 2004, "Handbook of Slope Stabilization", Springer-Verlag, Berlin, Heidelberg, Germany.

128. Parkash, Surya. "Earthquake Related Landslides in the Indian Himalaya: Experiences from the Past and Implications for the Future." Landslide Science and Practice. Springer Berlin Heidelberg, 2013. pp. 327-334.

129. Parkash, Surya. "Capacity Development for Landslides Risk Reduction in India." Landslides: Global Risk Preparedness. Springer Berlin Heidelberg, 2013. pp. 369-383.

130. Parkash, Surya. "An Overview of the National Guidelines for Management of Landslides with Particular Reference to Infrastructure Projects." Water and Energy International 69.3 (2012): 29-37.

131. Parkash, S. "Chapter 2–Good Practices in Landslides Risk Management-An Example from Uttarkashi, Uttarakhand State, India." Total Disaster Risk Management: Good Practices. Asian Disaster Reduction Centre (ADRC), Japan (2009): 3-4.

132. Parkash, S., Nair. S: November 2008: Status of Monitoring Studies for Slope Movements - Indian Perspective., International Conference on management of Landslide Hazard in Asia Pacific Region.

133. Parkash, Surya. "Awareness and Preparedness Strategies for Community Based Disaster Risk Management with Particular Reference to Landslides." Landslide Science and Practice. Springer Berlin Heidelberg, 2013. pp. 265-270.

134. Popescu M.E. (2001). A Suggested Methods for Reporting Landslide Remedial Measures, IAEG Bulletin, 60, 1: 69-74.

135. Popescu, M.E. and Sasahara K. (2009) Engineering Measures for Landslide Disaster Mitigation, Landslides – Disaster Risk Reduction, pp. 609-631.

136. Prasad P.S., Kumar Kishor, Negi Indervir Singh and Kathait Anil (2013), " Design of Remedial Measures at Likhbir Slide on NH-31 A Near Sikkim" , Journal of Engineering Geology. (Communicated for Publication).

137. Practice Note Guidelines for Landslide Risk Management 2007" Ref: AGS (2007c). Australian Geomechanics.

138. Principles of Low Cost Engineering in Mountainous Regions, Transport Research Laboratory, ORN 16, 1997.

139. P.Jagannatha Rao, Kishor Kumar, G.L.S. Babu, R.K. Panigrahi (1998). Investigation, Instrumentation and Monitoring of Landslides at Powari, Kinnaur District (H.P) - A Case Study. Journal of Indian Roads Congress. New Delhi, Vol. 16. 1998.

140. P. Jagannatha Rao, Kishor Kumar, G.L.S. Babu, R.K.Panigrahi (1996). Investigation, Instrumentation and Monitoring of Landslides - A Case Study. Proc. of Indian Geotechnical Congress, Madras, 1996.

141. Ramesh. M.V., 2009; Wireless Sensor Network for Disaster Monitoring; Amrita Center for Wireless Networks and Applications; Amrita Vishwa Vidyapeetham; Amrita University; India.

142. Recommended Procedures for Implementation of DMG Special Publication Guidelines for Analyzing and Mitigating Landslide Hazards in California.

143. Report on "Investigation of Kaliasaur Landslide on National Highway-58 and Design of Control Measures for its Long-terms Stability", NRDMS, Department of science & technology (DST), 2010.

144. Roadway Slopes and Embankments, MDT, Geotechnical Manual.

145. Robert Y. Liang, 2007, Final Report: "Landslide Hazard Rating Matrix and Database", Vol. 1 of 2.

146. http://www.dot.state.oh.us/Divisions/Planning/SPR/Research/reportsandplans/Reports/2007/ Geotechnical/Vol. 1 Landslide Hazard Rating Matrix Database Final Report.pdf

147. Rockfall Protection - Problems and Solutions, maccaferri.

148. Rogers, D., Tsirkunov. V, 2012 : Costs and Benefits of Early Warning ; Global Assessment Report on Disaster Risk Reduction, GAR 2011, ISDR, World Bank.

149. Roy, K.D, 2009; Early Warning System for Landslides: A Satellite-Based Network System that Can Monitor All the Landslide-prone Sites of the Country From a Central Monitoring Station and Generate an Early Warning to Respective Places is now possible.

150. Salt. G; Alarm Criteria and Monitoring for Hazardous Landslides; Opening address to ISL Landslide Workshop 1988. Updated 1993.

151. Sikdar P.K., Kumar Kishor, Goyal Nitesh, Janarthanan G. (2002). Critical Review of Landslide Hazard Zonation Practices and Direction for Future. Proceeds of Indo-China workshop on Natural Disaster held at CRRI, New Delhi, Jan 21-23, 2002.

152. SafeLand Deliverable D4.8; Guidelines for Landslide Monitoring and Early Warning Systems in Europe – Design and required technology; 2012.

153. Savvaidis. D. P., 2003. Existing Landslide Monitoring Systems and techniques; University of Thessaloniki, Greece.

154. Scottish Road Network Landslides Study: Implementation.

155. Singh, Rebekah Gereldene, Landslide Classification, Characterization and susceptibility modeling in Kwazulunatal. p.29.

156. Slope Maintenance Manual 2008, Ministry of Public Works and Transport Roads Administration Division, Scott Wilson in association with Lao Consulting Group (http://r4d.dfid.gov.uk/PDF/Outputs/SeaCap/Seacap21_Slope maintenance manual.pdf

157. Sowers, G.F. and Royster, D.L. 1978. “Field Investigation,” Landslides: Analysis and Control, Transportation Research Board, Special Report 176, National Academy of Science, Washington, DC, pp. 81-111.

158. SOA (1995), State of the Art report: Landslide Correction Techniques, Special Report No.15, Highway Research Board Publications, Indian Roads Congress, New Delhi.

159. SOA (2012), State of the Art: Use of Jute Geotextiles in Road Construction and Prevention of Soil Erosion/Landslide, Special Report No 21, Highway Research Board Publications, Indian Roads Congress, New Delhi.

160. SOR (2014), State of Art Report: Design and Construction of Rockfall Mitigation Systems, Indian Roads Congress, New Delhi.

161. Specification for Road and Bridge works, Fifth Revision, MORTH.

162. Pradhan Shanal, Kumar Kishor, Gangopadhaya S (2013), Landslide Hazard Database and Inventory- Focus on a Suitable Methodology for India, Journal of Indian Roads Congress, Paper no. 603 October - December 2013.

163. Kimothi Shivashish, Kumar Kishor and Mathur Sudhir (2010), Rockfall and Subsidence on Mumbai—Pune Expressway. International Journal of Geo-engineering Case Histories, Vol, 2, Issue 1, p. 24-38.

164. The International Geotechnical Society, UNESCO working party for World Landslide Inventory, 1993.A suggested method for describing the activity of a landslide, Bulletin International Association of Engineering Geology.

165. The International Geotechnical Society, UNESCO working party for World Landslide Inventory, 1993. Multilingual Landslide Glossary, Canadian geotechnical society, BiTech publisher Ltd.

166. The Japan landslide society, National Conference of Landslide Control http://www.tuat.ac.jp/~sabo/lj/ljap3.htm.

167. The Landslide Handbook— A Guide to Understanding Landslides, U.S. Geological Survey.

168. Thiebes. B., 2012; Landslide Analysis and Early Warning Systems; Local and Regional Case Study in the Swabian Alb, Germany.

169. Thomson, J.C. and Ingold, T. S. (1986), “Use of Jute Fabrics in Erosion Control”, Report of the International Trade Centre, UNCTAD/GATT.

170. Turner, A.K. and Schuster, R.L. (editors), 1996. Landslides: Investigation and Mitigation. Transportation Research Board. U.S. National Academy Press.

171. UUN/ISDR Platform for the Promotion of Early Warning http://www.unisdr.org/ppew/ppew-index.htm.

172. United States Environmental Protection Agency, Office of Water, “Storm Water Technology Fact Sheet, Turf Reinforcement Mats,” EPA 832-F-99-002.

173. U.S. Department of Transportation, Federal Highway Administration (FHWA 1998), Manual for Design and Construction Monitoring of Soil Nail Walls.

174. Varnes, D.J., 1978, Slope Movement Types and Processes, in Schuster, R.L., and Krizek, R. J., eds., Landslides— Analysis and Control: Transportation Research Board Special Report 176, National Research Council, Washington, D.C., p. 11–23.

175. Walter. K., Niemeyer, F., Bill, R, 2008: Geosenser Enablement Web in Early Warning Systems for Landslides, Faculty for Agricultural and Environment Sciences, Institute for Management of Rural Areas, Professorship for Geodetics and Geoinformatics.

176. Wendeler, C., McArdell, B., Volkwein, A., Denk, M., Gröner, E., 2008, Debris Flow Mitigation with Flexible Ring Net Barriers - Field Tests and Case Studies. WIT Trans. Eng. Sci. 60: 23-31.

177. WMO 2010 : Guidelines on Early Warning Systems and Applications of Nowcasting and Warning Operations, PWS-21, WMO/TD No. 1559, Geneva, Switzerland (Available through the WMO website at the following weblink : http://www.wmo.int/pages/prog/amp/pwsp/publicationsguidelines_en.htm.

178. Wold, R.L. Jr. and Jochim, C.L. 1989. Landslide Loss Reduction: A Guide for State and Local Government Planning. A Colorado Geological Survey Special Publication #33.

179. WP6: Monitoring, Prevention and Management of Specific Effects of Climate Change con Nature; Slope Monitoring Methods- A state of the Art Report (2008).

180. Yadav O.P., Kumar Kishor, Panigrahi R.K.and Mathur Sudhir (2003). Stabilisation of Cut Slope Through the Use of Soil Nailing Technique. National Seminar on Disaster Management with Specific Reference to Landslides and Avalanches organized by BRO, October 2003, New Delhi.

181. Yadav O.P., Kumar Kishor, Panigarhi R.K., Singh Kanwar (2001). Stabilization of Cut Slope through the Use of Soil Nailing Technique. Proceeds of the Workshop on Reinforcing Technologies for Slope Stabilization and Control of Landslides Jointly Organized by CRRI and CDMM, at CRRI, New Delhi.

ANNEXURE - 1

Table 1 Some of the Disastrous Landslides

Uttarakhand:		
Date/Year	**Location**	Damage
1867 and 1880	Nainital	There have been two major landslides on the Sher-ka-Danda slope in Nainital. The 1180 landslide took place on account of rainfall and an earth tremor. A large portion of the range and the buildings were swept away in minutes. The slide permanently filled a portion of the Naini lake.
July 1968	Garhwal Himalaya	Active Kaliasaur slide- continuous damage to road
July 1970	Alaknanda	Landslide dam broke, huge boulders were thrown far and wide causing wide spread damage, nearly 15 vehicles and 35 lives were lost. There were numerous landslides in the region, besides reactivating the old ones.
Sep 1985	Haridwar-Badrinath Road	First time in 1920, then in 1952, 1963, 1964, 1965 and a major landslide in 1969, 1970, 1971, 1972 and Sept 1985 and so on. The Kaliasaur Landslide is the most persistent and regular occurring Landslide.
1991	Garhwal	Large number of landslides, rock dislodgements, subsidence and ground fissures have been observed at several places.
Aug 2nd, 1997	Joshimath-Badrinath road	Lambagarh landslide has damaged about 250 m stretch of road out of which 40 m of road was totally disappeared
14 Aug 1998	Okhimath	69 people killed
18 Aug 1998	Malpa, Kali river	210 people killed. The heap of debris created were about 15m high. The village was wiped out in the event.
1999, 2004, 2009	Joshimath-Badrinath road	In 1999 and 2009, The Lambagarh Landslide has reoccurred. Both these events lead to closer of road for a period of 10-15 days at a single span and for many days, intermittently, in the year. In 2004, Heavy landslides hit Lambagarh area, 17 people were killed, 300 meter long road washed away.
26th July 2009	Gopeshwar, Chamoli district,	two laborers were killed and 4 injured
9 Aug 2009	Pithoragarh	43 killed in mudslide and 2 villages completely destroyed
8th Sep 2009	Almora district	three persons were killed and five others injured, two vehicles damaged
19 Aug 2010	Bageshwar district	18 children killed and more than 30 trapped in the rubble of school building
19 Sept 2010	Garhwal, Kumaon	Landslides and cloudburst triggered by incessant rain claimed 37 lives in Garhwal and Kumaon regions. Also over 5,000 tourists and pilgrims were stranded on Char Dham Yatra routes.
Oct 2010	Kaliasaur	Heavy rainfall triggers the notorious Kaliasaur landslide causing closures of NH-58 between Srinagar and Rudraprayag for more than a month, 3 people were killed, nearly 100 meter long road completely covered by debris.
2011	NH 58 and Rishikesh-Gangotri road	The landslides blocked the roads at Several places and stuck the thousands of tourists as well, 15 lives have claimed.
August 2012	Asi Ganga valley, Uttarkashi district, Uttarakhand	29 person were killed, connectivity to 85 villages were disrupted
September 2012	Okhimath, Rudraprayag District, Uttarakhand	69 persons were killed while 15 people were injured; more than 70 houses were reportedly damaged.

June 2013	Uttarakhand	169 person were killed, 4021 person were missing, 19780 houses affected, 145 bridges were damaged or washed off, 2070 roads connectivity were disrupted.
Himachal Pradesh:		
Date/Year	**Location**	**Damage**
Sep 1968	Himachal Pradesh	Active Maling slide- 1 km of road and a bridge washed out
Dec1982	Himachal Pradesh	Near Solding nallah 3 bridges & 1.5 km length of road washed away
1986	Himachal Pradesh	88 dead due to sliding
March 1989	Himachal Pradesh	Nathpa, 500 m road section is frequently damaged during successive year
Sep 1995	Kullu	22 persons killed and several injured about 1 km road destroyed
15 Aug 2007	Dharla village,	Around 60 people were dead in the cloudburst. It brought down 20-25 ft high huge boulders
14 Feb, 2010	Kinnaur district	six persons were killed and 14 others injured in a landslide on the bank of river Satluj at Kachsthal village of Kinnaur district
22 Oct, 2010	Rohtang pass	More than 2,500 tourists were stranded at 12,500 feet after sudden snowfall closed the crucial Pass.
March 2011	Kullu District	The incessant snowfall and rain resulted in landslides and blockage of Kullu-Manali road and Chandigarh- Manali highway, more than 500 vehicles, including tourists were trapped, between the landslides
Aug 2011	Mandi District	Two persons were killed and 15 others injured & 12 houses were damaged due to landslides,
August, 2012	Himachal Pradesh	Two buildings collapsed at Shimla, Rock fall or landslides have affected more than 60 road routes
June 2013	KinnaurDistrict,Himanchal Pradesh	10 persons were killed, 300-400 families have been badly affected in the district
Jammu & Kashmir:		
Date/Year	**Location**	**Damage**
1913 to 1993	NH 1A, from Jammu to Srinagar at km 138	It is an old and notorious landslide. Nashri landslide causes disruptions and blockage of the road several times in the same year. Often many vehicles and equipments are buried in the huge debris generated.
Almost annual feature	NH 1A, Jammu- Srinagar Highway	Almost every year landslides occur at the Khuni Nallah site destroying vital bridges and disrupting the traffic and the communication system.
Jan 1982	Nashri, J&K	Active slide from 1953. Every year road and communication network is damaged
Jan 1994	Kashmir	National Highway 1A severely damaged.
June 1995	Malori Jammu	6 persons killed, NH 1A damaged
2003	Himalaya	25 dead
2005	Verinag,Qazigund, Ramsu, Anantnag,Poonch	250 killed in an avalanche
8th Feb 2010	Narundi area of Uri sector of north Kashmir's Baramulla district	five houses damaged, one person killed, 6 injured
25th May 2010	Uri in Baramulla district	damaged several houses, Over 100 people trapped
5 & 6 Aug, 2010	Leh, ladakh fragmented	145 persons dead, floods and mudslides triggered by cloudburst at Leh, Ladakh. Several villages along the Chang-la pass, the world's second-highest motorable road, were feared washed away.

Sept 2010	Dharam-Tharad area, Ramban district.	Landslide destroyed 42 houses, a mosque and a government school.
18th April 2011	Doda District	6 person killed, 1 injured
Sept 2011	Jammu-Srinagar NH.	Over 300 vehicles have been stranded at various points.
East India:		
Date/Year	**Location**	**Damage**
1968	Bihar, Bengal	1000 killed in the mishap of sliding
August 1993	Kalimpong, WestBengal	40 people killed, heavy loss of property
16th Aug 2009	Darjeeling, West Bengal	17 people killed and many injured, 500 houses damaged
26-27th March 2011	Darjeeling District, West Bengal	Two people were killed and an equal number were injured
Sep 2011	Sevoke To Rangpo Along NH31-A, West Bengal	15 Seismogenic landslides have occurred and badly breached the road respectively
South India:		
Date/Year	**Location**	**Damage**
Nov.1992	Nilgiris, Tamil Nadu	Road network and buildings damaged, Rs.5 million damage estimated
Nov. 1993	Nilgris, Tamil Nadu	Occurrence of Landslide is widespread in Nilgiris. During 1993, about 408 landslides occurred of which Marapplam is the severest in terms of loss and magnitude 40 people killed, property worth several lakhs damaged.
9 Nov 2001	Amboori, Kerala	38 persons killed, damage to houses. A large number of huge sized boulders, some of them weighing 5 to 10 tonnes rolled down during the slide.
10th Nov 2009	Ooty region, Tamilnadu	killing at least 39 people, demolished nearly 300 tinned roof mud huts
10th-11th Nov 2009	Nilgiris, Tamil Nadu	543 landslips have occurred, 816 houses razed to debris, 600 hectares of crops and road revetments (in 145 places) has been devastated. Above all, 43 precious lives lost and over 1,100 people have been left homeless.
West India:		
Date/Year	**Location**	**Damage**
June 1994	Varundh Ghat, Konkan Coast	20 people killed, breaching of ghat road damaged to the extent of 1km.
1996	Karnataka,Andhra Pradesh,Maharastra	48 killed
19 and 25 June, 2010	Valmikinagar, Kurla, Mumbai and Harnai, 180 kms from Ratnagiri , Maharashtra	Seven houses damaged, killed eight persons.
30 July 2014	Malin Village, Ambegaon taluka, Pune district, Maharashtra	134 persons were killed in which 50 men, 64 women and 20 children (as of 4 August 2014), 44 houses were damaged.
North- East India:		
Date/Year	**Location**	**Damage**
1948	Assam	500 people killed in landslide occurrence
1957, July 1966 and 1972	Gangtok-Siliguri road, Sikkim	The seismicity of the area and the rainfall both are the triggering factors of this slide. An average rainfall of about 3000 mm is common in the slide area. The slope uphill of the road is a complex landform.
1978	Northeastern	64 killed in the slide
July 1991	Assam	300 people killed, road and buildings damaged.
June 1993	Aizawal	Four persons were buried

July 1993	Itanagar A. P.	25 people buried alive 2 km road damaged
Aug1993	Kohima, Nagaland	200 houses destroyed, 500 people died, about 5 km road stretch was damaged.
May 1995	Aizwal Mizoram	25 people killed road severely damaged
1997	Gangtok, Darjeeling	51 killed in the slide
2005	Assam	12 dead in the landslide
20th Aug 2009	Sombaria and Daramdin, west Sikkim	Two persons were killed and 10 others were injured
21 April, 2010	Arunachal Pradesh	At least 12 people have died in Arunachal Pradesh due to landslides triggered by heavy rains on 21st April 2010. Landslides have cut off road links at Lohit, Upper Siang, Dibang Valley, Anjan and East Kameng districts.
28th June, 2010	Shillong, Meghalya.	One killed and at least seven others were injured
12th Sep, 2010	Lakhimpur, Dhemaji, Golaghat and Bongaigaon Districts, Assam	Two persons were killed and about 300,000 displaced in flash floods and landslides
23rd March 2011	Guwahati	five persons were buried alive and two seriously injured
Sept 2011	Sikkim	158 Seismogenic landslides have occurred along the Singtham – Dickchou road, Rangrang-Dickchou road and North Sikkim Highway.
September 2012	Sikkim, Assam and Arunachal Pradesh, North East India	26 persons were killed, eight people are missing
May 2013	Aizawl, Mizoram	17 people lost their precious lives; 6 people were injured; 11 houses completely swept away; 6 houses partially destroyed and 17 vehicles were buried under the debris.

* The data listed above is quit partial and just indicating of the severity of the phenomena in our country. Anybody likes to us data for their own purpose suggested to revalidate the authenticity of the data.

Table 2 The Main Satellite Imagery Sources which May be Applicable to Landslide Investigations are Summarized below:

The use of Remote Sensing techniques used for investigation of landslides
Aerial Photography (Orthogonally-rectified digital aerial photography)
Identifies the presence of existing failure scars and debris run out. Identify pre-conditioning factors for failure (where visible at the resolution of the photography).
Low cost Unmanned Aerial Vehicles (UAV)
This approach enables reveals high-resolution digital surface models of landslides. Digital surface models (DSMs) are generated using a new feature-based surface reconstruction approach which does not require any ground control point information and enables surface models to be generated from UAV-based remote sensing without ground based measurements.
Object-Oriented Analysis (OOA)
OOA has the potential to accurately and meaningfully detect landslides by integrating the contextual information to image analysis, therefore reducing the time required for creation of landslide inventory for large areas.
Optical Satellite Imagery (Thematic Mapper)
The Landsat series of satellites operates the Thematic Mapper instrument. Landsat-7 now offers a 15 m resolution panchromatic band which enables mapping scales to 1:25,000. The Indian, IRS-1C with 5 m pixels improves mapping scales to 1:10,000. The IKONOS satellite, available since early 2000, offers data which provides 1 m ground resolution imagery and enables mapping scales of 1:2000 or greater. The French SPOT satellite provides 10 m resolution panchromatic data and the ability to acquire stereo image pairs. At these scales individual flow lobes, ground fissures and subtle morphology indicative of potential peat landslides may be resolvable.

Microwave (Synthetic Aperture Radar Interferometry, In SAR)
Radar imagery, at different wavelengths and polarization, can be obtained from both satellite and aircraft. Radar data can be acquired during the night or day and effectively 'sees' through cloud. Currently available SAR (synthetic aperture radar) data includes ERS with 25 m spatial resolution, RADARSAT with 10-15m spatial resolution and stereo capability, and JERS with 18 m spatial resolution. These data enable interpretation at a range of scales from regional, to local and include vegetation type, moisture content, debris sizes etc.
Multispectral Video
Multi-spectral video cameras operate at the visible to near infra-red portion of the spectrum and can be mounted on low-flying aircraft. They can generate pixels of less than 1m ground resolution and are therefore suitable for large mapping scales. Field spectra obtained from in-situ measurements are used to determine different classes of iron oxide precipitates from the air and, by inference, the different pH levels of drainage systems.
Hyper spectral
Airborne hyper spectral scanners are much more complicated and expensive instruments than multispectral video. They can be mounted on low-flying aircraft. Remotely sensed multi-spectral data have been shown to be of considerable use for landslide investigations. Uses include the mapping of geological units in areas of poor exposure through estimation of soil moisture content, the estimation of soil thickness prone to landslides and the mapping of geomorphological features of landslides at the regional scale and the local scale.
Stereo photogrammetry
In the method of stereo photogrammetry, a satellite acquires two images of the same ground scene within a relatively short period of time, so that it can view surface features have not significantly changed. These images can be processed to get topography from the stereo pair of images. The series of stereo pairs offers a 3 dimensional evolution of the landslide over time.
Terrestrial laser scanners
Generates a high resolution topographic model DEM of the study area. The laser system is combined with a differential GPS system and calibrated colour digital cameras(infrared cameras can also be fitted) to produce surface topographic data and photographic imagery.
Global Positioning System (GPS)
GPS is a useful tool for detecting first stage disaster and further mitigation. It can detect movement of cm/yr., and aid in determining the boundary of the landslide area. Monitors can be placed anywhere you can access, and they are relatively easy to operate. But precision is affected by the number of observable satellites present, the obstruction of the observation point, and the monitoring of installed GPS receivers which have been placed out in the field.

Table 3 A Variety of Remotely Sensed Images Available from Different Sensors with Varying Radiometric, Spatial and Spectral Resolution

Satellite	Sensor	Resolution(m)
IRS P6 Resourcesat-1	AWiFS	56
	LISS III	23.5
	LISS IV	5.8
LANDSAT 5	MSS	80
	TM	30
LANDSAT 7	ETM	30
	PAN	15
IRS-1D	PAN	6
Terra	ASTER	15
IRS P6 Resourcesat-1	LISS IV	
RISAT (SAR system)	C-Band SAR	1-50
SPOT IV	PAN	10 m
IKONOS	PAN	1 m pan

Satellite	Sensor	Resolution(m)
	XS	4
IRS P5 CARTOSAT 1	PAN(stereo)	2.5
CARTOSAT 2	PAN(stereo)	0.81
SPOT 1, 2, 4	XS	20
	PAN	30
SPOT	XS	10
	PAN I	5
	PAN 2	2.5
QUICKBIRD	XS	2.44
	PAN	0.61

- ✓ Recent advances in new techniques, such as Object-Oriented Analysis (OOA), a platform for integration of different types of data (spectral, elevation and thematic) has the potential to detect landslides automatically in a better way than the pixel, based methods, by incorporating a multitude of landslide diagnostic features.
- ✓ The availability of a new generation of high resolution of optical satellite imageries (eg. World View, GeoEye, SPOT-5, Resourcesat, Cartosat, Formosat and ALOS-PRISM) has caused a paradigm shift in the use of Earth Observation (EO) data for landslide studies.
- ✓ Digital Elevation Models (DEM) produced from overlapping aerial photographs or stereoscopic satellite images are the major sources of elevation data for landslide studies. A DEM is useful for estimating the volume of landslides by an elevation change analysis. Shaded relief images produced from a DEM obtained from light detection and ranging (LIDAR) have proven to be very suitable for generating landslide inventories under forest areas in hilly regions and to refine the boundaries of landslides prepared during field investigations.
- ✓ SPOT-5 HRS (high resolution stereoscope) data have been shown to be valuable for DSM generation. Cartosat-1 and ALOS-PRISM are other more recent sources of along track stereoscopic data. They are more advantageous than methods employed by SPOT1-4 AND IRS-1C/D Satellites, which are frequently affected by atmospheric differences between the images.
- ✓ New generation satellites such as Cartosat-I have considerable advantages over airborne stereo imagery, due to their high periodicity, synoptic view, high data quality, relatively low cost, and quick extraction of DEM.
- ✓ The main satellite remote sensing methodology used for measure accurate land displacement is the InSAR (Interferometric Synthetic Aperture Radar) technique.
- ✓ Quickbird satellite sensors produce very detailed elevation models that are considerably more cost-effective than the equivalent areal coverage of airborne LiDAR or SAR.

Table 4 Showing Advantages and Disadvantages of Survey Methods with their Respective Diagrams

Surveying Methods	Advantages	Limitations	Diagram
Elevations by optical leveling	Fast, particularly with self-leveling equipment Uses widely available equipment	First order leveling requires high-grade equipment and careful adherence to standard procedures	
Trigonometric leveling	Long range; fast and convenient; can be done simultaneously with traversing	Accuracy is influenced by atmospheric conditions; requires a very accurate measurement of zenith angle	—
Distance measuring by taping	Direct measurements	Requires clear, relatively flat surface between measuring points and reference datum; movement can only be measured in one direction; tape should be checked frequently against standard; except for short measurements, taping has been replaced by EDM.	
Electronic distance measurement (EDM)	Long range; fast and convenient; very accurate.	Accuracy is influenced by atmospheric condition	
Offsets from baseline using theodolite and scale	Direct measurements.	Requires baseline unaffected by movement	
Laser beam leveling and offsets	Faster than conventional optical methods; readings can be made by one person	Seriously affected by air turbulence, humidity, and temperature differential; requires curvature and refraction corrections beyond about 200 ft	
Traverse lines	Useable where direct measurements are not possible	Accuracy decreases as number of legs in traverse increases; traverse should be closed if possible	—

Surveying Methods	Advantages	Limitations	Diagram
Triangulation	Useable where direct measurements are not possible	Requires accurate measurement of angles and baseline length	—
Photogrammetric methods	Can record movement of hundreds of potential points at one time for determination of overall deformation pattern	Weather conditions can limit use; interpretation requires specialist; for good accuracy the baseline should not be less than one-fifth of the sight distance	
Global positioning system (GPS)	Intervisibility between points is not required. Can be used at any time of the day or night and in any weather. can be set to trigger a warning device; very accurate.	Requires open sky line of sight. Accuracy of height component is 2 times lower than positional accuracy. Energy supply needed on every station.	
Total Station	They provide 3D coordinate information of the points measured	The requirement to have an unobstructed line-of-sight between the instrument and the targeting prism. Vertical refraction errors can reduce the accuracy of the height information that may be obtained from the total station measurements.	
(ADAPTED FROM DUNNICLIFF, 1993)			

Table 5 Main Characteristics of Current and Forthcoming Microwave Satellites

Satellite	Sensor	Space Agency	Operational Since	Band	Wavelength (cm)	Polarization	Resolution Range (m)	Scene with (km)	Orbital Elevation (km)
ERS-1	AMI	ESA	1991	C	5.7	VV	26	100	785
ERS2	AMI	ESA	1995	C	5.7	VV	26	100	785
Radarsat-1	SAR	RadarSat Int	1995	C	5.7	HH	10-100	45-500	798
JERS-1	SAR	NASDA	1992	L	23.5	HH	18	75	568
Envisat	ASAR	ESA	2002	C	5.7	HH/VV	30-150	56-400	800
Radarsat-2	SAR	RadarSat Int	2005	C	5.7	QUAD-Polb	3-100	50-500	798
Alos	PALSAR	NASDA	2004	L	23.5	All	7-100	40-350	660
TerraSAR-X	TSX-1	DLR/Infoterra GmbH	2006	X	3	All	1-16	5-100	514
Cosmo/Sky Meda	SAR-2000	ASI	2005	X	3	HH/VV	1-100	10-200	619

Table 6 Piezometers for Measuring Positive pore Water Pressure

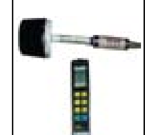
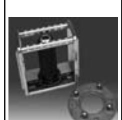
Types	Role	Suitability	Advantage	Disadvantage	Photographs
Open-hydraulic-Standpipe/ Casagrande	Determination of soil pore pressures	It involves no inaccessible moving parts: this makes them particularly well suited to long-term monitoring works.	Cheap, simple to read & maintain. In-situ permeability measurement possible. Direct measurement of water level. There are no buried "sensing" components.	Vandal damage often irreparable.	
Closed Hydraulics (Twin-tube Hydraulic)	Long term monitoring of Pore water pressures in embankment dams	Because of two tubes, if gas has entered the system through the filter, tubing, or fitting, the gas must be removed by flushing easily.	Simple device, moderately expensive, reliable, long experience record. Short lag time. Minimal interference with construction operations. In-situ Permeability measurement possible.	Gauge house usually required. Regular de-airing necessary. A terminal enclosure is needed to contain the read-out and flushing arrangement. This enclosure must be protected from freezing and from vandalism.	

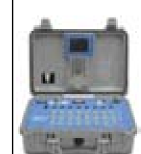
Types	Role	Suitability	Advantage	Disadvantage	Photographs
Diaphragm Piezometer	Pneumatic piezometers can be successfully used in zones that are either partially saturated or in zones that may dry out for short periods.	When pore water pressures are to be read, air or nitrogen is admitted to one line, but is prevented from flowing up the other line by a blocking diaphragm in the tip.	Fairly cheap. Components are not affected by electrical transients. The use of gas rather than water means there are no problems of elevation and freezing.	No method of checking if pore water or pore air pressure is measured. The presence of moisture in the connecting leads will affect the readings.	
	Vibrating wire piezometers should be considered at sites where frequent groundwater measurements are required.	More accurate measurements of pore water pressure are occasionally called for, requiring the installation of vibrating wire piezometers, which may be read remotely.	The VW piezometer provides rapid response in all types of soils. Suitable for unattended monitoring with a data logger. The device can be used to measure small sub-atmospheric pore water pressures. No freezing problems. Transmission over long distances.	There is no independent means of recording the position of the sensor and therefore if large settlements are likely care must be taken in the interpretation of results. Expensive. Zero reading liable to drift and cannot be checked	
Electrical resistancez	It can be used as profiling piezometer for measuring pore water pressure at many points.		Moderately complex device, expensive. Simple to monitor. Very short lag time. Elevation of readout independent of elevation of tips and piezometric levels. No freezing problems. Easily automated.	The principal disadvantage of being unable to undertake calibration checks. As above.	

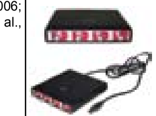
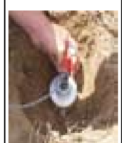
Table 7 The Choice of a Piezometer Should be Based on the Factors Summarized in the Table Below

Instruments	Range	Response Time	Reading Time	Readout	Remote Access	Data Log	Main Advantages	Main Limitations	Main Cost of Installation
Standpipe	Depth of stand pipe	Slow	Minutes	Water level indicator. Size and weight depend on reel capacity.	No. Reading is obtained at top of standpipe. Not normally, just possible with bubbler or float system	No	Simplicity. Nothing to go wrong.	No remote access.	Borehole. Components are the least expensive of any type of piezometer
VW	50, 100, 250, 500 psi	Fast	Seconds	Portable readout. Lightest, smallest	Yes. Signal cable can be run to remote readout station. Yes, but special cable required	Yes	Easy to read. Simple grout-in installation. Remote access.	Long horizontal runs of cable should be protected from electrical transients	Borehole. Components are more expensive than pneumatic or standpipe.
Pneumatic	180 psi	Fast	5 minutes with 200 feet of tubing. Longer times with longer tubing.	Portable readout. Large and heavy because of internal tank.	Yes. Tubing can be run to remote readout station. Yes Some head loss over long distance	No	Remote access. Not affect by electrical transients.	Slow reading time	Borehole. Components are more expensive than pneumatic or standpipe.

Table 8 Geotechnical, Geophysical Instruments Used for Surface and Subsurface Deformation

	GEOTECHNICAL						GEOPHYSICAL					
	Type	Advantage	Disadvantage	Role /purpose	Accuracy/ Precision	Photographs	Type	Advantage	Disadvantage	Role/Purpose	Acquisiton Parameters	Photographs
Surface	Extensometer/ crack gages/ convergence gages	Inexpensive and has a precision ranging from ± 0.01 to ± 0.1 inches.	The principal limitation of mechanical crack gages is the relatively short span length between the pins. 1D displacement vector cannot measure out of line displacements.	devices used to monitor changes in distance between two points at the ground surface or on a structure	precision ranging from ± 0.01 to ± 0.1 inches.		Seismic Seismic refraction profiling	Determines depths to strata and their characteristic seismic velocities	May be unreliable unless strata are thicker than a minimum thickness, velocities increase with depth, and boundaries are regular. Information is indirect and represents average values	All are based on the fact that the elastic properties of earth materials determine the velocities of waves propagating through them	Seismic relection- Vp, Vs, 2D vertical sections Seismic refraction- Vp, Vs	
	TWSI Digital Wire Extensometer	Ensures an evolutional up-grade to conventional analog transducer. Low power RF with transmission ranging up to 2 km (with optional module) reduces the equipment and installation cost and power requirement	—	Detects the signal of displacement based on the amount and rate to identify different levels of landslide event and provides an alarm signal. Provides the signal periodically so as to ensure stable operation and also indicate the power status.	± 0.1 % F.S.		Direct seismic (uphole, downhole, and crosshole surveys)	Obtains velocities for particular strata, their dynamic properties, and rock-mass quality	Data are indirect and represent averages; may be affected by mass characteristics	—		
	Digital Tape extensometer	Lightweight and rugged design which can be easily read and operated by one person. One unit reads at many locations. Robust and proofed against mechanical damage under reasonable field conditions		The tape extensometer is used to determine changes in the distance between pairs of reference points, including monitoring deformations in underground openings.	0.05 -0.2 mm		Electrical and electromagnetic Electrical resistivity	Locates boundaries between clean granular and clay strata, groundwater table, and soil rock interface	Difficult to interpret and subject to correctness of the hypothesized subsurface conditions; does not provide engineering strength properties	It is based on measuring the electrical potentials between one electrode pair while transmitting a direct current between another electrode pair	electromagnetic methods were recently used for landslide investigation, mainly for determining the geometrical limits of the unstable mass.	
	Crackmeter	Reliable & accurate. Simple to install. Simple to read. Rugged construction. Low cost.	Crack monitoring may not provide an accurate indication of displacement in areas of extensive cracking, plastic surface deformation, or areas of developing (or retrogressing) instability.	These devices measure the displacement between two points on the surface that are exhibiting signs of separation. They can be very simple and low-cost devices, so they are often used as warning systems	0.3 mm		Electromagnetic Conductivity profiling	Locates boundaries between clean granular and clay strata, groundwater table, and rock-mass quality; offers even more rapid reconnaissance than electrical resistivity	Difficult to interpret and subject to correctness of the hypothesized subsurface conditions; does not provide engineering strength properties	—	r, 1D horiz. profile and 2D map	
	Tiltmeter	Tiltmeters very accurately measure inclination relative to gravity, either at a discrete point or along a baseline. Horizontal tilt meters are particularly versatile as they may be manufactured on site using readily available low cost materials.	Bubble tiltmeters however they can be sensitive to temperature fluctuations	Tiltmeters are used to determine the direction of movement, to delimit the areas of deformation and to determine the mechanism of movement (e.g. slumping or slope creep). They can also provide advance warning of accelerated slide movement and quantify the effectiveness of landslide repairs	precision is typically ± 50 arc-seconds; and the temperature sensitivity is typically in the range of 2 to 3 arc-seconds/°F (Dunnicliff, 1993).		Microgravity	Extremely precise, locates small volumes of low density materials utilizing very sensitive instruments	Use of expensive and sensitive instruments in rugged terrain typical of many landslides may be impractical; requires precise leveling and elevation data; results must be corrected for local topographic features; requires detailed information on topography and material variations; not recommended for most landslide investigations	They can detect areas of low density in relatively large landslides.		—

	GEOTECHNICAL					GEOPHYSICAL						
	Type	Advantage	Disadvantage	Role /purpose	Accuracy/ Precision	Photographs	Type	Advantage	Disadvantage	Role/Purpose	Acquisiton Parameters	Photographs
	Long range distance meter		The maximum range over which the instrument can provide sensible readings is 30 m	Long range displacement meters are used to measuring changes in the distance between two points over a span of several meters .	+- 1mm		Ground-penetrating radar	Provides subsurface profile; locates buried objects (such as utility lines), boulders and soil-bedrock interface	Has limited penetration in clay materials and shales.	This method appears to offer important potential for rapid subsurface profiling	e, 2D vertical sections	
	--Raingauge		————				Seismographs	Multichannel seismographs allow more sophisticated data filtering, recording and processing. Enhancement of the signal to noise ratio.	Multichannel seismographs are more complex and expensive	Used to record shock-wave travel times between a source and a receiver, or geophone, over a series of selected distances.		
	Rod extensometer (Lateral deformation)	Provides high accuracy and precision data as it avoids issues such as creep and kinking associated with tensioned wire systems. Multiple rod installations within one borehole, Single Point or, Multiple Point. Electric head allows unattended monitoring by a data logger	Anchor depth is limited by rod material and orientation of rods. Free movement of horizontal rods can be restricted by friction and by pinching due to vertical movements. Placement is important because the rod extensometer monitors movements along the axis of a borehole. In contrast, the inclinometer can report deformation over a wide area.	Rod extenso meters serve to measure lengths between one or more anchor points and a reference point.			Seismic Tomography	allows lateral P-wave velocity variations to be determined	Compared to classical seismic refraction, the technique requires much more travel-time data and field effortThe versatility of event information is highly dependant on the sensitivity and layout of the geophone array, and interpretation can be limited by poorly considered installations		Vp, 2D vertical sections	
Surface	TDR (TIME Domain Relflectometry) (Lateral deformation) Inclinometer (Lateral deformation)	cost effective installation. prolong the lifetime of inclinometers. Continuous data collection possible. remote data collection. measurement of subsurficial deformations. delivers a insight (surface of rup-ture/position of slip plane, width and type of deformation zone)	proper grouting (especially in soil) . only applicable to localized shearing deformation (narrow shearing zone) . quantitative measurements are still a challenge (movement rates > 2 cm/a) . no information on direction/ orientation of deformation . combination with surface measure-ments necessary	TDR cable surveillance can detect very thin or localized shear zones. Use of TDR in combination with inclinometers or tiltmeters allows remote operation as well as sensing of both gradual tilt and localized deformation. TDR typically detects ground movement when it is in excess of 1 in. (25 mm).			Direct Current Geoelectric System	Low acquisition time for a single potential measurement. Thus only high quality data points can be selected for the inversion without any loss in resolution. Consequently a subsurface coverage about ten times higher compared with conventional arrays is reached within a much shorter time.	————	The determination of the distribution of the subsurface resistivity is the purpose of direct cur-rent (DC) geoelectrical measurements. The aim is the correlation of ground resistivity with geological parameters.		

	GEOTECHNICAL						GEOPHYSICAL					
	Type	Advantage	Disadvantage	Role /purpose	Accuracy/ Precision	Photographs	Type	Advantage	Disadvantage	Role/Purpose	Acquisiton Parameters	Photographs
	Inclinometer (Lateral deformation)	Provide accurate indication of soil deformation with time. Inclinometers generate more data than do other types of sensors. Provides profile of settlement over broad area. Does not interfere with site operations. In-place version provides real-time data when connected to data logger	The main disadvantage of this type of instrument is that curvature is only observed in one axis.	inclinometers are used for monitoringlandslides/slopes, to detect zones of movement and establish whether movement is constant, accelerating, or responding to control measures. These instruments help for the determination of slip surfaces or zones of movement and they reveal the depth of the failure plane(s).	± 0.05 to 0.5 inches per 100 feet for force-balance accelerometer transducers, ± 0.02 to 1 inch per 100 feet for bonded resistance strain gage transducers, and ± 0.1 to 0.5 inches per 100 feet for vibrating wire transducers (Dunnicliff, 1993).		Microseismic monitoring	Microseismic data may be used to monitor the temporal and spatial evolution of slope instabilities. Spatial location of microseismic events can provide important in-formatio regarding the location, propagation, and mechanics of unstable areas. The most detailed data from microseismic inves-tigations can provide information on individual microseismic events and aid the interpretation of the instability mechanism	The versatility of event information is highly dependant on the sensitivity and layout of the geophone array, and interpretation can be limited by poorly considered installations	It has been used to identify active areas of slope deformation and provide details on the precursors to failure (Amitrano et al., 2007; Amitrano et al., 2005; Meric et al., 2007). Microseismic monitoring is unique in that it can provide information on the entire subsur-face volume.	Microseismic monitoring systems generate a significant quantity of data, in the order of 1Gbyte per day (Roth et al., 2006; Spillmann et al., 2007)	
	Geophones			geophone is a device which converts ground movement (displacement) into voltage, which may be recorded at a recording station. The deviation of this measured voltage from the base line is called the seismic response and is analyzed for structure of the earth.			Seismic Reflection		this method requires a bigger effort to deploy the geophone layouts, particularly in the conditions of rugged topography, making the technique time consuming and costly	The major interest of seismic reflection profiling is its potential for imaging the geometry of the landslide structure, such as the internal bedding or the rupture surface(s) and the robustness of processing tools compared to tomography.		
	Borehole Extensometrs (vertical deformation)			Borehole extensometers are used to measure rock displacement which may take place as a consequence of movements in natural slopes.	The accuracy of the device depends on the type of mechanical or electrical transducer used to measure change in the anchor location.							
	Probe extensometer	Reliable, accurate, sim-ple to install and operate. Any number of points along a borehole can be monitored at little extra cost. Magnetic targets avai-lable for monitoring settlement in boreholes and fills. Telescopic coupling for access tubing allows high settlement / heave			+- 1mm