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Slope Remediation Techniques and Overview of Landslide Risk Management

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Abstract

Slope failures are common in many parts of the world which occur due to manifold reasons and they result in huge losses to the respective locals. This study evaluates the initiatives that can enhance the safety of slope by considering the remedial measures to deal with the factors causing slope instability and discusses the application of risk management strategies to address the problems that can cause the slope to fail. The methods for the remediation of slope include modification in slope geometry, drainage, use of retaining structures and internal slope reinforcement. This study also discusses the risk management process which is a hierarchical procedure that includes assessment and control of risk through different techniques in order to manage the uncertainties associated with the slope. It has been observed that the implementation of risk management strategy aids in the proper identification of risk and its severity which dictates the selection of appropriate remedial measure for the rectification of slope. For reducing the number of landslides, this study suggests the use of risk based strategies to curtail the chances of slope failure.

Keywords: Slope Failures; Slope Geometry; Drainage; Retaining Structures; Internal Slope Reinforcement; Risk Management Process.

1. Introduction

Landslides have resulted in the loss of human lives and properties in many parts of the world. To combat landslide risk, a wide range of risk mitigation measures are available. These range from hard engineering measures of slope stabilization and landslide protective works to soft community means of public education. Stabilization works aim at reducing the likelihood of failure of a slope whereas the other measure reduces the risk by minimizing the consequences of slope failures. The range of slope stabilization works may be categorized as follows [1]:

a. Surface protection and drainage
b. Subsurface drainage
c. Slope regarding
d. Retaining structures
e. Structural reinforcement
f. Strengthening of slope-forming material
g. Vegetation and bioengineering
h. Removal of hazards
i. Special materials and techniques

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It is a fact that slope failures account for enormous losses every year, both compensatory and non-compensatory. These failure events occur due to varying reasons which predominantly include design inaccuracies, lapses in construction, poor drainage system and lack of maintenance. It is observed that misperceptions towards the technical aspects of slope also contribute to the failure. Some of the misperceptions highlighted by Gue and Fong are given below [2].

1.1. Soil Tests Showed that Slope is Safe

It is irrational to rely solely on tests as soil is a very complex material and its properties can vary even at a very short distance. Remarkably detailed investigations are required to propose safety. In fact, they are the source of getting design variables used in analysis and designing of the slopes.

1.2. Heavy Rain Cause Slope Failures

It is not always the case because properly designed slopes will not fail unless water table and pore water pressure exceeds the design limit. Rainfall may catalyse the instability of slope but if the slope is designed as per requirement then the failure is unlikely.

1.3. Retaining Walls Always Prevents Slope Failures

This is only possible if retaining walls are designed according to required specifications, fulfilling every design criteria which is usually not satisfied in un-engineered walls.

1.4. Slopes Are Maintenance Free

Maintenance activities like clearing the debris from drains, covering up the erosion spots are essential. Blocked drains create excess water pressure which ultimately leads to slope failure. Poor maintenance or non-maintenance of slopes has significant contribution in decreasing the slope stability.

For slope stabilisation, Thompson et al., 2005 [3] proposes that slope reinforcement and the use of structural pile elements can be an effective slope remediation alternative when conventional remediation practices (e.g., improved drainage) fail to consider the causal factors leading to slope instability (e.g., strength loss due to weathering). An experimental research program was aimed at developing a rapid, cost-effective, and simple remediation system that can be implemented into slope stabilization practices for relatively shallow (<5 m) slope failure conditions. The results of the study shows that piles installed in failing slopes will arrest or slow the rate of slope movement.

The study of Ashour and Ardalan, 2012 [4], presents a new procedure for the analysis of slope stabilization using piles. The developed method allows the assessment of soil pressure and its distribution along the pile segment above the slip surface based on soil–pile interaction. The proposed method accounts for the influence of pile spacing on the interaction between the pile and surrounding soils and pile capacity.

The slope strengthening initiatives are taken on the basis of the factors that affect the stability of slope and the level of risk they are posing. In order to address the risk associated with the slope there is need to apply the risk management strategy for reducing the chances of failure. The risk management takes the output from the risk assessment, and considers risk mitigation, including accepting the risk, reducing the likelihood, reducing consequences e.g. by developing monitoring, warning and evacuation plans or transferring risk (e.g. to insurance), develops a risk mitigation plan and possibly implements regulatory controls. It also includes monitoring of the risk outcomes, feedback and iteration when needed. Landslide risk management involves a number of stakeholders including owners, occupiers, the affected public and regulatory authorities, as well as geotechnical professionals, and risk analysts. It is an integral part of risk management that the estimated risks are compared to acceptance criteria (either quantitative or qualitative). Geotechnical professionals are likely to be involved as the risk analysts, and may help guide in the assessment and decision process, but ultimately it is for owners, regulators and governments to decide whether the calculated risks are acceptable or whether risk mitigation is required [5].

Landslide risk management comprises an estimation of the landslide risk, deciding whether or not the risk is tolerable, exercising appropriate control measures to reduce the risk where the risk level cannot be tolerated. In a more global context, landslide risk management also refers to the systematic application of management policies, procedures and practices to the tasks of identifying, analyzing, assessing, mitigating and monitoring landslide risk [6].

2. Objectives of the Study

The objectives of the study are as follows:

1) To discuss the potential remedial works that can be employed for maximizing the stability of the slopes

2) To explore the approaches for risk based evaluation of slope and discuss the strategies for landslide risk management

3. Causal Factors of Landslides

There are two primary categories of causes of landslides: natural and human caused. Sometimes, landslides are caused, or made worse, by a combination of the two factors. The natural causes have three major triggering mechanisms that can occur either singly or in combination with water, seismic activity, and volcanic activity. Effects of all of these causes vary widely and depend on factors such as steepness of slope, morphology or shape of terrain, soil type, underlying geology, and whether there are people or structures on the affected areas [7] .

With regards to the human causes, populations expanding onto new land and creating neighborhoods, towns, and cities are the primary means by which humans contribute to the occurrence of landslides. Disturbing or changing drainage patterns, destabilizing slopes, and removing vegetation are common human-induced factors that may initiate landslides. Other examples include over steepening of slopes by undercutting the bottom and loading the top of a slope to exceed the bearing strength of the soil or other component material. However, landslides may also occur in once-stable areas due to other human activities such as irrigation, lawn watering, draining of reservoirs (or creating them), leaking pipes, and improper excavating or grading on slopes [7].

Table 1. A brief list of landslide causal factors [8]

1. Ground Conditions
(1) Plastic weak material
(2) Sensitive material
(3) Collapsible material
(4) Weathered material
(5) Sheared material
(6) Jointed or fissured material
(7) Adversely oriented mass discontinuities (including bedding, schistosity, cleavage)
(8) Adversely oriented structural discontinuities (including faults, unconformities, flexural shears, sedimentary contacts)
(9) Contrast in permeability and its effects on ground water contrast in stiffness (stiff, dense material over plastic material)
2. Geomorphological Processes
(1) Tectonic uplift
(2) Volcanic uplift
(3) Glacial rebound
(4) Fluvial erosion of the slope toe
(5) Wave erosion of the slope toe
(6) Glacial erosion of the slope toe
(7) Erosion of the lateral margins
(8) Subterranean erosion (solution, piping)
(9) Deposition loading of the slope or its crest
(10) Vegetation removal (by erosion, forest fire, drought)
3. Physical Processes
(1) Intense, short period rainfall
(2) Rapid melt of deep snow
(3) Prolonged high precipitation
(4) Rapid drawdown following floods, high tides or breaching of natural dams
(5) Earthquake
(6) Volcanic eruption
(7) Breaching of crater lakes
(8) Thawing of permafrost
(9) Freeze and thaw weathering
(10) Shrink and swell weathering of expansive soils

4. Man-Made Processes
(1) Excavation of the slope or its toe
(2) Loading of the slope or its crest
(3) Drawdown (of reservoirs)
(4) Irrigation
(5) Defective maintenance of drainage systems
(6) Water leakage from services (water supplies, sewers, storm water drains)
(7) Vegetation removal (deforestation)
(8) Mining and quarrying (open pits or underground galleries)
(9) Creation of dumps of very loose waste
(10) Artificial vibration (including traffic, pile driving, heavy machinery)

4. Remedial Measures for Slope

Slopes are all around us in the urban environment, and the soil on some of these slopes may be inherently unstable. Old, natural slopes in rural and forest areas have often developed a degree of stability over time. But artificial slopes within urban areas that are part of developments, or that are adjacent to infrastructure such as roads and railways, can be less stable, and may require stabilization [9].

Movement of soil and rock down unstable slopes due to gravity is called mass wasting; surface movement resulting from the effects of wind and water is called erosion. Both processes can affect the safety of people living or working on or near slopes, and on the quality of water for people living in the wider area. The expansion of urban areas, and associated deforestation and construction activities, are increasing the area of unstable or vulnerable slopes [9].

Decision on selecting an appropriate slope stabilisation method requires thorough evaluation of the existing slope conditions and assessment of the prevailing causes that are responsible for the instability of the slopes. Once the causes of slope stability are identified, the appropriate remedial measure for slope is selected on the basis of feasibility, stability and economy. These remedial measures are helpful in minimizing the chances of approaching slope failure by addressing its cause.

Precautionary action means detection of landslide prone area, early warning signs and slope assessment techniques to take necessary measure for their remediation. Government agencies put forward different policies while private sector also takes initiatives to prevent the consequences of slope failure by developing its own guidelines. The remedial methods proposed by Broms and Wong are divided into three main categories [10].

4.1. Geometrical Method

This method is simple and cheaper in cost but require sufficient space. Slope safety can be enhanced easily to convert steeper slopes into gentler ones. This method can be executed by trimming the slope or making the slope free from extra loading. Backfilling of toe also lies under this category.

By changing the geometry of a steep slope to a gentler slope either flatten the slope or backfill at the toe of slope, the stability of a slope can be increased. This method is easy and most cost effective. However, it depends very much on the site condition. As there are existing building at the site, this method cannot be adopted [11].

4.2. Drainage Method

This method usually works in combination with other methods. Drainage method is viable in those conditions where proper maintenance of surface and sub-surface drains is performed.

Saturation of subsoil and pore water pressure building up are major factors causing the instability of slope. With the proper design of surface and subsurface drainage system, the chances of building up pore water pressure and saturation of subsoil can be minimized and therefore the stability of slope can be increased. However, as a long term solution to increase the stability of slope, this method suffers greatly because the drainage systems must be maintained if they are to continue to function It is always easy to maintain the surface drains but very difficult for the subsoil drains. This method is generally used in combination with other methods [11].

4.3. Retaining Structures Method

This method is quite expensive but flexible in nature. In this method retaining structures are used to withstand against the pushing forces of the soil masses. Retaining structures have different varieties such as gravity and cantilever retaining wall, contiguous bored piles and sometimes method of soil nailing is also used to stabilize slopes.

Retaining structures include gravity types of retaining wall, cantilever retaining wall, contiguous bored piles, caisson, steel sheet piles, ground anchors, soil nails etc. This method is generally more expensive as compared with the other methods. However, it is always the most commonly adopted method in remedial works due to its flexibility in a constraint site. For this project, the remedial work can only be carried out within the boundary, a restrained structure is inevitable in order to stabilize and reinstate the failed slope [11].

The remedial works proposed by Popescu, [12] carry four groups namely slope geometry, drainage, retaining structures and internal slope reinforcement. The initiatives in the category of slope geometry involve fundamental changes that include removing material from the landslide driving area and reducing the slope angle. The remedial works in the class of drainage involve different methods which include providing boreholes, wells and water removal techniques. The category of retaining structures includes provision of different types of structure to give stability to the slope while the category of internal slope reinforcement includes providing anchors, micro piles and soil-nailing.

Table 2. Landslides Remedial Works [12]

Slope Geometry
Adding (counter weight berm or fill) material to stability maintain area
Removing material from landslide driving area (light weight fill)
Reducing the slope angle
Drainage
Surface drains for diversion of water (pipes and ditches)
Shallow or deep trench drains having filled with free draining Geo-materials
Vertical boreholes for self-draining
Vertical wells for gravity draining
Buttress counterforts of coarse grained materials
Sub vertical and sub horizontal boreholes
Drainage tunnels, galleries drainage by siphoning
Electroosmotic dewatering, Vacuum dewatering
Retaining Structures
Gravity retaining walls
Gabion walls, Crib-block walls
Passive piles, Piers, Cassions
Cast in situ reinforced concrete walls
Reinforced earth retaining structures
Buttress counterforts of coarse grained materials
Rock fall attenuation or stopping systems
Protective rocks or concrete blocks against erosion
Internal Slope Reinforcement
Rock bolts/ Anchors/Electroosmotic anchors
Micro piles
Soil nailing

5. Risk Based Planning of Slopes

The study of Li et al., 2009 [13] refers to the soil cut which are subject to deterioration and prone to failure especially during the monsoons and as a consequence of seismic activity. In this regard, risk based stabilized planning is developed to counter the deteriorating slopes.

Risk based stabilization planning is used as a tool in decision making to minimize the chances of slope failure and its consequences. The proper follow up of stabilization programme not only covers slope deterioration but also reduces the maintenance expenditure. Level of risk (whether in in acceptable limits or not) can be easily estimated and reduction measures can be adopted through this risk based methodology in case of intolerable risk levels.

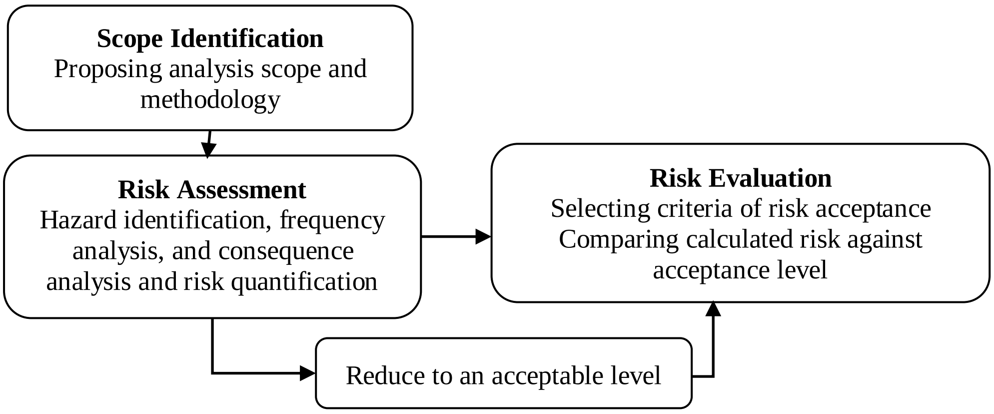

Figure 1. Risk based stabilization planning [13]

Landslide risk assessment and management encompasses the judgment of the level of risk [14]. Risk level has to be checked, whether if it is in an acceptable mode or not, and implement the correct controlling measures to minimize the risks. It needs the following issues to be discussed.

- Probability of land sliding
- Run out behaviour of landslide debris
- Vulnerability to people and property by the landslide
- Management strategies and decision-making.

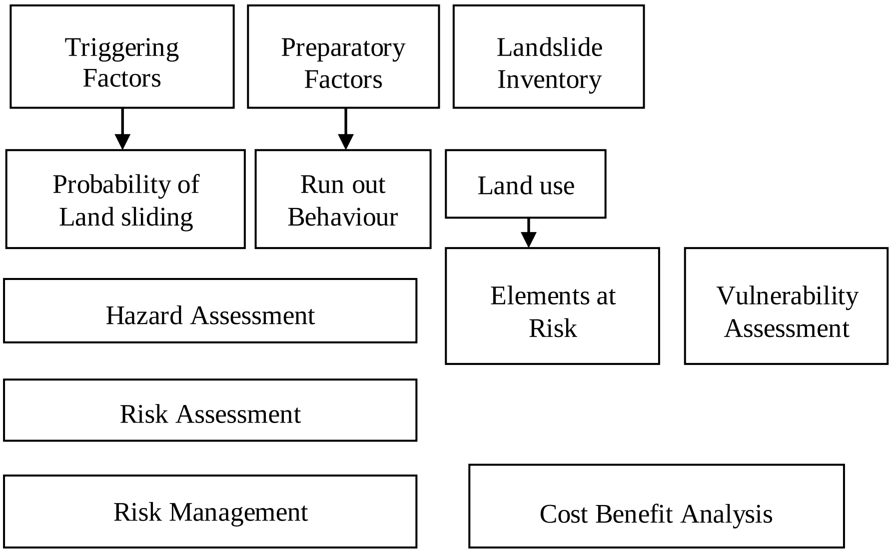

Figure 2. Landslide Risk Assessment and Management [14]

6. Risk Management Framework

A general risk management framework proposed by Shong [15] is shown in Figure 3. It involves four basic steps of:

- Planning
- Execution
- Review
- Improvement

In calculating the risks, equally important parameter of probability of slope failure has to be carried out first. Same is put forwarded by Shong [15] when discussing about the steps involved in determining slope stability assessment. In slope stability assessment, the major stages involved are given below:

- Evaluation of silhouette/shape with the condition of the slope.

- Weighing the external effect and their impact. For example surcharge, accidental loads on slopes or embankments.
- Determination of slope conditions for different time periods and selection of logical stability measures.

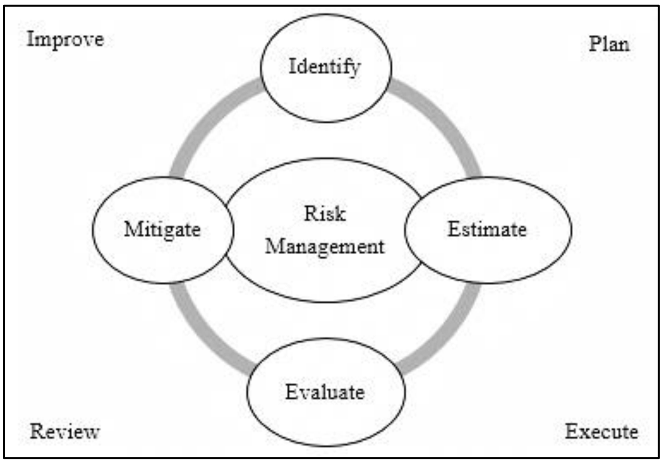

Figure 3. Risk Management framework [15]

A baseline approach for managing risks in developing countries is also proposed by Kjekstad [16]. The approach is divided into three pillars:

- Assessment or prediction of hazards and risks
- Mitigation measures for landsides
- Contribution of cooperation and support by other developed countries.

According to Nadim and Lacasse [17], the optimal risk mitigation strategy involves the following:

- Identification of possible landslide triggering scenarios, and the associated hazard level
- Analysis of possible consequences for the different scenarios
- Assessment of possible measures to reduce and/or eliminate the potential consequences
- Recommendation of specific remedial measure and if relevant reconstruction and rehabilitation plans
- Transfer of knowledge and communication with authorities and society

6. Probability of Slope Failure and Risk Management

The discussion on probability of slope failures as temporal and spatial probability has been done before by Van Westen et al., 2006 [18]. Spatial probability is directly concerned with static environmental factors of slope strength; material properties and depth while temporal are referring to dynamic factors such as rainfall intensities and drainage.

Another study discussed about the probability of failure of site specific slopes by Dai et al., 2005 [14]. In actual probability of failure is referring to the probability of the safety factor having value less than 1. The performance function $G(X)$ is the main function of the slopes which differentiates between the safety and the failure. If $G(X) > 0$ failure will not take place and $G(X) < 0$ shows that the safety level is alarming which means most probably it will fail. The performance function $G(X) = 0$ is a limit state boundary. It separates the two states. Once the performance function is established by taking all input variables involved in the stability analysis, the probability of failure can be calculated using statistical tools. Mathematically performance function is defined as:

$$G(X) = F(X) - 1 \quad (1)$$

or

$$G(X) = R(X) - S(X) \quad (2)$$

Where safety factor is denoted by $F(X)$, $R(X)$ is the resistance and $S(X)$ is the load.

Slope stability is one of the main controlling factors of landslide. Assessment of the existing slope in relation to risk is more meaningful in relation to the landslide issues. It is imperative to follow a risk management planning process which is a hierarchical procedure for the assessment of risk which indicates that the basic approach remains the same. In this connection, Canadian Standard Association [19] produced an extensive model about the assessment and the control of the risk which is given below.

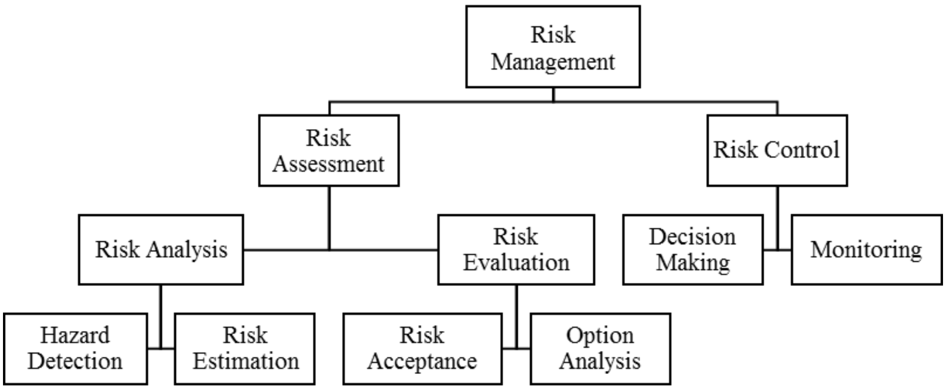

Figure 4. Risk Management process [19]

7. Consequence Estimation of Slope Failure

It is one of the most significant components used to evaluate risk. Unlike the identification of hazard, it is performed quantitatively and provides information about the significance level of the probable effects. When consequence estimation is related to a particular accident, it is viable to decide from which aspect the safety and health of surrounding community can be affected. Consequence estimation can be performed by:

- Expert opinions/judgements
- Information about past incidences for comparison
- Consequence modelling

Wong et al., 1997 [20] proposed a consequence model which included slope features like slope angle and its height, landslide size and susceptibility to the affected amenities. The amenity is supposed to be at worst location and its degree of living is taken as below average. The anticipated consequences of failure (potential loss of life PLL) are measured according to real size/actual size of failure and the actual location of the facility.

Mathematically potential loss of life (PLL) can be defined as:

$$PLL = \sum \left\{ \begin{array}{c} \text{Expected} \\ \text{no of} \\ \text{fatalities} \\ \text{directly by} \\ \text{reference} \\ \text{landslide} \end{array} \right\} \left\{ \frac{\begin{array}{c}\text{Actual size} \\ \text{of landslide}\end{array}}{\begin{array}{c}\text{Size of} \\ \text{reference} \\ \text{landslide}\end{array}} \right\} \left\{ \begin{array}{c} \text{Vulnerability} \\ \text{factor} \end{array} \right\} \tag{3}$$

The definition of vulnerability according to the glossary of risk-assessment terms of the International Society of Soil Mechanics and Geotechnical Engineering is the extent of losses to a specified element or combination of elements within the area hit by the landslide hazard. It is expressed on a scale of 0 (no loss) to 1 (total loss).

Vulnerability may perhaps be the propensity to loss (or the probability of loss) and not the degree of loss [21]. According to Li et al., [21] model definition of vulnerability is:

"Vulnerability (V) is defined as a function of the hazard intensity associated with exposed elements at risk and the resistance ability of the elements to withstand a threat".

Mathematically it can be summarized as:

$$V = f(I\ R) \tag{4}$$

Where:
I = intensity of risk exposed elements
R= ability of the elements to bear the threat

Basically the intensity refers to the two components including dynamic intensity factor taking velocity into consideration and geometric intensity factor which is governed with size related features of landslides. In the context of different localities, intensity can be modified with debris depth factor and deformation factor. Considering the resistance factor, it is indirectly dependent on construction material, age and height.

A study by Uzielli et al., 2008 [22] anticipated a univocal logical framework for quantitative evaluation of substantial vulnerability to landslides, which is expressed as a function of landslide intensity and susceptibility of vulnerable elements. Mathematically its definition is:

$$V = f(I\ S) \tag{9}$$

Vulnerabilities of persons, structures and persons in structures have also been estimated. Kaniya et al., 2008 [23] has shown the methodology for its estimation using first-order second-moment method. This method is mostly to be used for approximation of regional landslide risks because of the involvement of comprehensive indices such as impact spatial ratio, population density and per capita GDP.

8. Discussion

In slope stability analysis, risks and uncertainties related to properties of that particular soil has to be investigated in more rigorous manner. Uncertainties associated with the soil properties are basically the output of insufficient or inaccurate data, errors propagated by different testing techniques or different statistical operations. Due to composite nature of soils, the spatial variation in its properties are obvious and it is in actual the product of natural geological processes.

Risk of landslides can be quantified through likelihood of slope failure and the losses occurred. When slope stability problems are measured, the prime factor is to conclude the safety level of that particular slope. An accurate determination of safety level should appropriately deal three geotechnical basics that work with slope stability, geometry, pore pressure and strengths [24].

It is necessary to adhere to a proper risk assessment plan for managing the risks associated with landslides. It essentially comprises of evaluation of risk likelihood and its possible consequences which leads to the estimation of risk. In case, if the risk is found to be high compared to a limiting value, revision in the work is required to prevent the imminent failure.

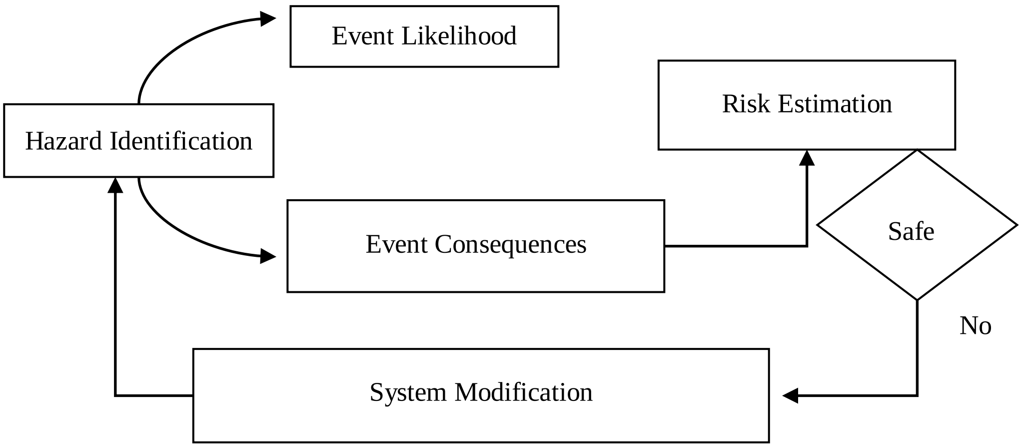

Figure 5. Risk Assessment Plan [24]

8. Conclusion

It has been established that landslides are responsible for prodigious losses every year which includes both compensatory and non-compensatory. Through various investigations it is clear that the landslides are triggered by several factors however, their chances can be minimized by employing a risk management strategy to cope with the factors causing slope instability and to take appropriate remedial measures for their rectification. The benefit of adhering to a risk based strategy is that it identifies the vulnerability to slope as a result of various factors by locating the risk and evaluating its intensity which leads to the selection of proper mitigation technique and reduction in the chances of slope failure. To curtail the landslide events, this paper suggests the use of risk based strategies to figure out appropriate solutions for the prevention of landslides.

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