Landslide and its Investigation Techniques

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Introduction

The site specific study of landslide is generally undertaken after the occurrence of a slide with a view to suggest the most appropriate ameliorative measures for stabilization of the slide. Though the Earthquake event which is related to the evolutionary process of our great planet, 'The Earth', is beyond the control of the scientists at least with the present stage of knowledge, it has become by and large possible to understand almost all the causative factors and the triggering agents giving rise to numerous landslides every year in our country during the monsoon period and at times during earth tremor. If we make an effort to understand the reasons of our failure for controlling landslides in our country, we must honestly confess that it is due to our strong belief in readymade solution but not in in-depth study to evolve a permanent solution to this problem. Another important difficulty faced in slope stabilization is that the investigating agency is not the implementing authority. As a result there is no feed back and the efficacy of the suggested remedial measures remains unknown to the investigating agency after its implementation. Besides, there are several instances when suggested remedial measures were implemented partially and the slide recurred during the next monsoon period taking away all the structures built for preventing further sliding. Sometimes projects are contemplated for stabilization of landslides funded by the Central or the State Agencies but at the end of the project generally no feed back is available rendering it impossible to assess the ultimate outcome of the completed project. Besides, the site specific studies of landslides are not generally undertaken adopting a complete scientific approach. This is mainly because there is neither a state of the art paper nor a standard guideline/BIS Code on the site specific study of landslide. It is a fact that it is not possible to lay a firm guideline for Landslide Investigation and its treatment as the geoenvironmental parameters and triggering agents responsible for inducing slope instability vary from terrain to terrain and site to site. There are multifarious approaches for carrying out detailed geotechnical investigation of a landslide to achieve the ultimate goal of stabilization of a slide. Research and Development in the field of site specific study of landslide should continue side by side. But in India there are hundreds of reported occurrences of landslides of variable dimensions in the Himalayan Mountainous Tract, North Eastern part, Western Ghats & Nilgiri Hills in the southern parts of the country. The Research and Development programme may be formulated for the in depth study of some of the devastating landslides. But the prerequisites for the study of these vast numbers of landslides are to adopt a commonly accepted easily applicable procedure so that the exact cause/causes and mechanism of failure are well understood and the most appropriate eco-friendly remedial measures can be evolved for stabilization of these landslides. Taking into consideration the occurrences of huge numbers of landslides in our country, it is impracticable to stabilise all these slides. Initially, the most conspicuous, devastating slides posing high risks to life and property may be selected for this purpose. Subsequently, more slides may be shortlisted on the basis of consideration of elements at risk and the degree of risk posed by these slides.

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This paper embodies a brief description of morphology of a typical slide, broad classification of landslide, causes of landslide, with special emphasis on the technique of site specific study of a landslide, stability analysis, rock slide data presentation technique by streograhic projection and remedial measures. Besides, Landslide Hazard Zonation and Landslide Inventory have also been discussed in brief.

Morphology of a landslide

The different components of a landslide (Fig. 1) are documented below:

- **Crown** : Topmost part of a landslide
- **Toe** : Bottommost part of a landslide
- **Tension Cracks**: Cracks aligned parallel with the width and occurring near and above the crown of a slide.
- **Longitudinal Cracks** : Cracks running parallel to the long axis of a slide
- **Transverse Cracks**: Cracks aligned askew to the long axis of a slide.
- **Slide Scar**: Top edge of a slide showing a well defined line of displacement of material.
- **Striation lineation:** Striation marks on the slide surface depicting the signature of direction of movement of the dislodged slope forming materials (overburden slide).
- **Zone of Depletion (Depression):** A zone just below the slide crown developed due to the removal of material during sliding.
- **Zone of Accumulation (Buldging)** : A zone below the depletion zone where the slide debris comes to rest temporarily.
- **Length of a Slide:** Crown to toe of a slide.
- **Width of a Slide:** Stretch across the length of a slide; variable from top to bottom; generally covers maximum stretch near the toe.

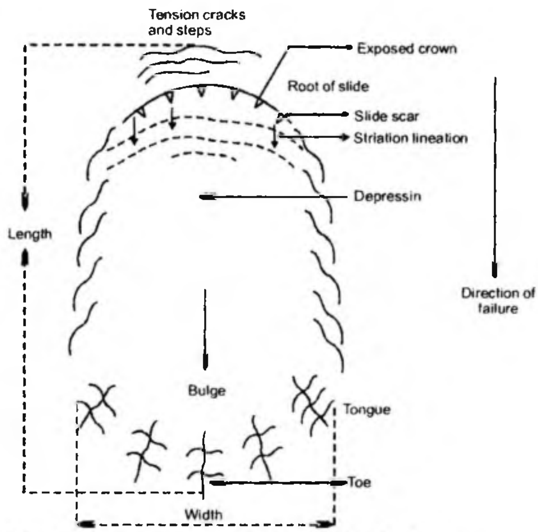


Fig. 1: Morphology of a typical landslide

Classification of landslides

The complex causes of landslides have made it very difficult to evolve a generalized classification of landslide. However, the most widely accepted classification of landslides is by Varnes (1978) who classified landslides according to the type of movement undergone on one hand and type of material involved on the other. A brief account of this classification is furnished below with little modifications: -

A. Type of material:

(a) Rock slide.

(b) Debris slide.

(c) Soil slide.

(d) Rock-cum-Debris slide.

(e) Debris-cum-Rock slide.

(f) Avalanche.

B. Type of movement (Translational, Rotational, Toppling, Fall, Creep, Spread, Flow etc.)

1. Rock slide

(a) Planar Failure

(b) Wedge Failure

(c) Toppling Failure

(d) Rotational Failure in intensely weathered rock

2. Debris/Soil slide

(a) Single rotational Failure

(b) Multiple rotational Failure

(c) Successive slip

(d) Debris flow

(e) Earth flow

(f) Soil creep

(g) Translational

(h) Spreading failure (by Liquefaction)

The plane of failure is called **slip surface** that may be circular, semicircular, uneven and planar. The main difference between translational and rotational movement is that in case of former the movement is essentially translational but in case of rotational slide the movement is circular/rotational or semicircular. The force system initiating a rotational slide decreases with increasing deformation due to backward tilting of the moving soil mass or rock. For a translational slide the force system causing the failure remains almost constant (Terzaghi,1950).The rotational movement is well documented by the concavity of the failure surface.

Causes of landslide

Landslide is a very complex process which may be attributed to its both internal and external causes (Terzaghi, 1950). The former includes mechanisms within the mass that bring about a reduction of its shear strength to a point below the external force imposed on the mass by its environment, thus inducing failure. External mechanisms operating outside the mass involved are responsible for overcoming its internal shear strength, including slope failure. However, a number of causative factors give rise to slope failure. Sometimes, it is very difficult to establish conclusively which one produced slope failure. Often, the final factor is nothing more than a triggering agent that set in motion a mass which was already on the verge of failure. The different causative factors leading to slope instability are furnished below:

(i) Steepening of slope developed by natural or artificial undercutting.

(ii) Poor shear strength of slope forming materials in natural moisture content or on saturation.

(iii) Parallelism between slope direction and dip direction of planar structure/ wedge.

(iv) Difference between the amount of inclination of slope and inclination of planar structure/wedge (Daylighted envelop).

(v) Hydrostatic pressure/Pore water pressure

(vi) Dissection Ratio/Drainage Density/ Stream Frequency

(vii) Overloading of slope.

(viii) Toe erosion.

(ix) Scouring of slope by streams or rivers.

(x) Liquefaction generated by earthquake shock/blasting/pile driving /excessive downpour.

(xi) Extensive deforestation, Hillslope excavation, mainly for roads.

(xii) Jhum cultivation.

(xiii) Solifluction/Permafrost.

(xiv) Storm effect on tall trees resting on steep hillslope.

(xv) Weathering of rocks.

(xvi) Tectonic fabrics in rocks.

(xvii) Lithology/ Compositon of rocks and overburden materials.

(xviii) Relative relief.

(xix) Average Annual Rainfall/Intensity of Rainfall.

(xx) Seismicity

(xxi) Finally combination of some of these specific causes.

Site specific study of landslide

The detailed study of a landslide is aimed at clearcut understanding and delineation of (i)nature and type of slide (ii) dimension of the distressed slope under the influence of the landslide (iii)dynamic behaviour of slide (iv) elements at risk (v) degree of risk involved to life and property (vi) run-out-characteristics of the slide (vii) causative factors leading to slope instability (viii) mechanism of sliding (ix)triggering factor/ factors accelerating the slide and (ix) slope instability status of the slide with a view to evolve the most appropriate corrective measures to contain the slide. It is a fact that most of the landslides in India occur generally in the Monsoon period. The intensity of Rainfall and Pore Water/Hydrostatic Pressures play a significant role in initiation of the mobilizing events. Generally, instrumentation in landslide is not done in India for the study of landslide with exception. But, porewater pressure can not be measured unless Piezometer is installed in a landslide. A tentative idea can be formed about the configuration of the ground water level if this level is available in individual borehole drilled for landslide investigation.. Consultation of various publications on the techniques of landslide investigation and its stabilization in India reveals that there is hardly any landslide which has been studied covering all the above mentioned aspects. Thus, it becomes difficult to evolve the most appropriate remedial measures for the stabilization of a landslide. The recurrence of known landslides every year during the monsoon period probably lends support to the aforesaid statement.

However, for describing the technique of Site Specific Study of landslide, all the landslides may be broadly classified into two types namely Overburden Slide and Rock Slide. There is a third variety designated as Rock Fall which is something different from the earlier mentioned two types of landslides.

Site specific study of overburden slide

The overburden slide may be broadly divided into two types namely Debris slide and Soil slide. Sometimes they form debris flow or soil flow due to sudden cloud burst or incessant downpour. The detailed study of the overburden slide involves the following steps:

Desktop work

i) collection of available geological map preferably on 1: 50,000 scale to acquire a basic idea regarding the disposition of different lithounits and tectonic set up of the area under review.

ii) collection of high resolution PAN or CARTOSAT scenes for at least consecutive three years from NRSA to demarcate the area likely to be affected by further sliding, understand the dynamic behaviour of slide, delineate modified slope condition in different periods from the preparation of DEM, record conspicuous geomorphological features depicting the surface manifestation of any active fault, documentation of catchment characteristics of any conspicuous nala draining the slope or any other important geomorphological features influencing stability condition of the slope.

Field investigation

- **Detailed Geological Mapping** of the landslide on 1:1000/500 scale or on suitable scale is carried out with Total Station / Theodolite depending on the dimension of the landslide preferably with 2m contour intervals. It is suggested that very careful observation should be made about the occurrences of the tensional cracks above the crown of a slide. These cracks sometimes appear much above the crown. Hence, the area to be covered by geological mapping is solely dependent on the judgement of an individual. As a geological map of a landslide serves as the baseline document, all efforts should be made to generate a most authentic geological map covering the following aspects :

i. shape and dimension of the slide, crown ,toe and width of the slide.

ii. disposition of last visible tensional cracks above the crown and longitudinal cracks on either side of the slide.

iii. orientation, spacings and openings of all the cracks.

iv. plunge of striation lineation on the scarp face often formed on the slide surface just below the crown of the slide.

v. disposition of accumulated, depleted zones and scarp faces.

vi. distribution of different sizes of debris.

vii. disposition, state of weathering, attitude of bedding, foliation and all other planar structures, litholological variation of rocks, if rocks are exposed.

viii. zones of toe erosion, deep gully erosion, courses of conspicuous nalas draining the slope.

ix. in case of soil slide, visual classification of soil type(clayey, sandy or approximate ratio of soil and rock pieces etc) generally get exposed on the scarp faces just below the crown of the slide.

x. locations of seepage, spring, and slushy ground.

xi. Zones of subsidence (with amount) during the investigation period.

xii. selection of sites for the collection of undisturbed soil samples; in case of debris slide, the locations where slope forming materials are almost free from rock pieces, are to be selected for collection of undisturbed soil samples.

xiii. all the features depicting break in slope e.g. number of steps formed within the slide zone, numbers of minor slides within the entire slide zone to be recorded as it gives an idea about the type of failure like single rotational/multiple rotational/ translational/multidirectional failure etc.

xiv. drawing of actual geological profile connecting the undisturbed zones both above the crown and below the toe of the slide; also cross-section/s at different levels, as required.

xv. locations of buildings/hutments/other civil engineering structures.

xvi. probable locations of boreholes, if proposed.

- **Subsurface Exploration:** The main purpose of subsurface exploration for the detailed study of a landslide is to delineate the contacts between overburden / weathered rock /fresh rock, compositional /lithological variation of overburden and rocks respectively, depth of ground water level, tentative depth of slip plane from the plane of separation between the disturbed and undisturbed slope forming materials along which the slope may again fail, depths of installation of instruments, if required. The subsurface exploration may be divided into two types (i) drilling and pitting (ii) geophysical survey. Drilling is generally done for conspicuous slides as it is a costly procedure. But geophysical survey (Resistivity/hammer seismic survey) should be carried out for all the slides though both the methodologies have their own limitations. No core can be recovered from wet drilling in overburden. Either dry drilling or SPT within overburden and wet drilling within rock is recommended. The main disadvantage of dry drilling in debris slide is that the drill bit gets worn off if some resistant rock blocks are encountered within the debris. As it can be tentatively understood about nature of the drilling medium from the drilling speed, it is suggested that wet drilling may be undertaken only when such resistant rock blocks are intercepted during dry drilling. After piercing through the rock block again dry drilling may be resorted to. Though it is a hazardous procedure, but there is no other reliable alternative to decipher the tentative slip surface. Similarly, SPT may not be feasible all through the thickness of the debris slide if rock blocks are encountered during this operation. If possible, permeability test in boreholes following BIS codes for overburden is also suggested. Otherwise, permeability test may be performed in the laboratory on undisturbed samples. Pitting may be done for small dimension shallow landslides to delineate the lithological variation and tentative slip surface, if possible, in the overburden slide. Geophysical survey, especially resistivity survey and hammer seismic survey, is widely used worldwide for subsurface exploration of landslide. It is sometimes said that geophysical survey connecting crown and toe of a landslide can not be done on a steep slope because of difficulties in the handling of instruments. In case of such locations, geophysical survey is carried out at different levels across the long axis of a landslide and finally longitudinal sections are developed from the crown to toe of a slide elsewhere in the world, e.g. in Canada.

- **Sampling and geotechnical properties:** Collection of slope forming material samples from the slide surface is an integral part of the study of a overburden slide. The main purpose of collection of undisturbed soil / matrix material samples (in case of debris slide) is to determine some physical and engineering properties like Shear Strength (angle of internal friction and cohesion), Unit Weight in Natural Moisture Content (NMC), Elastic and Plastic limit, Plasticity Index, Swelling Index, Grain Size Analysis, Porosity, Clay Mineralogy and Permeability test in the laboratory. At least three samples in steel tubes from a location must be collected for the determination of shear strength. It is recommended that such samples from three different locations from the slide surface should be collected to understand the variation in shear strength of the slope forming materials in different parts of the slide surface. Precaution should be taken to ensure that the sampling has not been done from the accumulated material. In case, of Boreholes, core samples from dry drilling or from SPT should be collected for this purpose.

- **Slope Stability Study:** It is not always economically viable to undertake subsurface exploration by drilling. On the other hand geophysical survey has its own limitations. The slope stability study of a overburden slide is done mainly for two purposes (I) to draw the most dangerous slip circle/plane of dislocation and (ii) to determine the Factor of Safety. But, it is not necessary that the failure surface will always occur along circular path. It may be along the contact between two contrasting lithological composition. If the configuration of the slip plane is known, the same study can be done without drawing a dangerous circle. However, this method is called "SWEDIDISH SLIP CIRCLE PROCEDURE"(Bishop, 1951, Fellenius, 1936, Taylor'1948).This study helps us to understand the stability status of the slope in terms of Factor of Safety and the tentative Depth of Plane of Dislocation (circular/semicircular) along which further sliding may occur. This also serves as the guiding factor to decide upon the length of perforated pipe for dewatering the slope and the depth of piles/ micro piles, sometimes recommended for stabilisation of landslides. However, it has been widely discussed in the literature that slope failure may not always occur along a circular path, particularly in case of heterogeneous composition of the slope forming materials. In this paper a simplified procedure of slope stability analysis described by Fellenius (1936) has been described. This is a **Limit Equilibrium Method (LEM)** which invokes no kinematical consideration regarding soil behaviour. That is why a shape of the potential slip surface is assumed for stability analysis. Hence, the selection of the shape of this surface is to some extent arbitrary. But in most of the Finite Element methods of slope stability analysis, the shape of the slip surface is assumed to be circular. The choice of a circular slip surface appears to be justified on the grounds that the computations are made easier.

There is another method of slope stability analysis called **Finite Element Method (FEM)** recently finding its much application in the field of soil mechanics study. This is alternatively known as the c-f reduction method of slope stability analysis. The basic difference between Limit Equilibrium Method and Finite Element Method is that slope stability analysis is done along an assumed slip surface in the LEM while in the FEM the most dangerous slip plane is determined by the incremental reduction in the c-f values, showing the lowest Factor of Safety. However, both the methods have their advantages and shortcomings too.

- **Drawing of dangerous circle:** No stability analysis is complete unless one has reached for the most critical shape and location of the shear surface. The requirements for this purpose are geological profile from above the crown to toe of the slide and slope angle (Fellenius, 1936). The slope angle can be read from the profile. Many softwares are available in the market now a days. It is a trial and error method. The circle showing the **lowest Factor of Safety** is the most dangerous slip circle. If the slope angle is known, the centre of the circle can be easily drawn (Fig.1a and 1b).In the Fig.1b the slope angle is 18°26' and corresponding á and â from the Fig.1a are 25° and 35° respectively. Thus in the Fig.1b, á and â are laid off from the toe of the slope and from a horizontal at the top of the slope respectively. Then the two outer sides of the angles will intersect in some point, O. With O as the centre, inscribe a circle having AO as radius cutting the slope line.

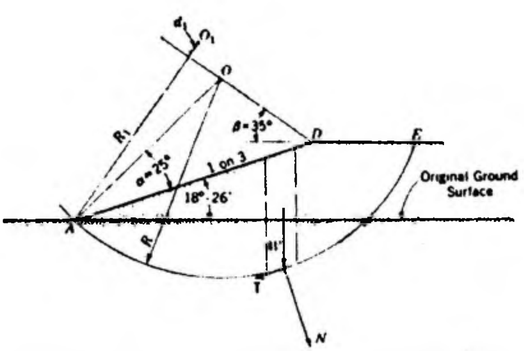


Fig. 1a: Method of analysis when dangerous circle passes through toe

- **Determination of Factor of Safety:** The factor of safety is a ratio between the resisting force preventing the movement and the driving force producing the movement along the shear surface. The area intercepted between the

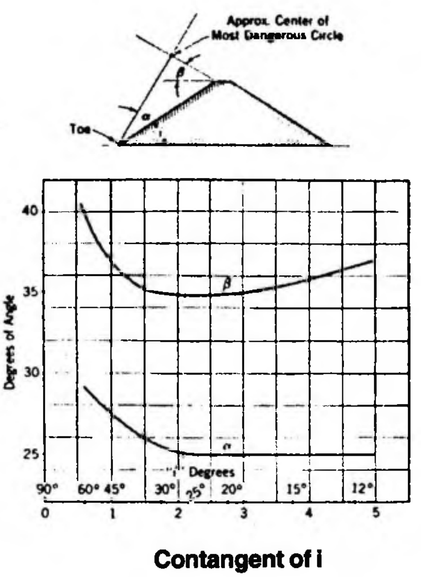


Fig. 1b: Angles a and b for different slopes to determine center of most dangerous circle which passes through toe

Analysis			
Section	D Depth of Section	Components of D	
		T	N
1	5.0	-0.8	5.0
2	15.0	-1.0	15.0
3	21.5	+1.2	21.4
4	25.8	+4.2	25.3
5	28.0	+7.4	27.0
6	28.0	+11.0	26.0
7	25.0	+12.0	22.0
8	18.5	+11.5	15.3
9	7.0	+4.7	5.0
		ΣT = 50.2	ΣN = 162

Weight of Slice = ΣD x 20 x 110#

ΣT Forces = ΣT Components x 20 x 110#
= 50.2 x 20 x 110# = 110.5k

ΣN Forces = ΣN Components x 20 x 110#
= 162 x 20 x 110# = 356k

$$\text{Factor of Safety} = \frac{\Sigma N \tan\phi + \text{Cohesion}}{\Sigma T} = \frac{356^k \times .58 + 10^k}{110.5} = \frac{216.5}{110.5} = 1.96$$

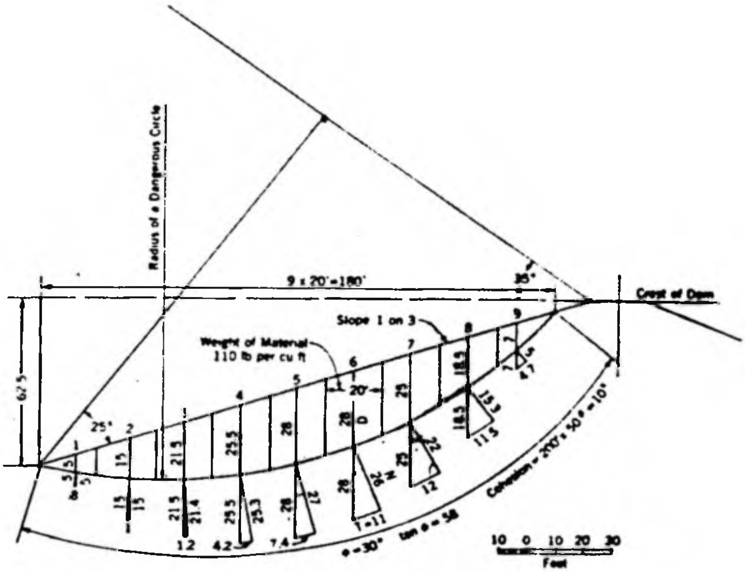


Fig. 1c: Example of dangerous circle analysis by slices

circumference of the circle and the slope line is divided into number of vertical slices preferably of equal width. The number of slices should not be less than five and generally not required more than twelve. The area and effective weight of each of the slices is determined, and a vertical line proportional to the total effective weight of the slice is drawn from its centre of gravity. At the circumference this weight is resolved into its normal and tangential components. This is followed for each slice. The next procedure is to add all the Normal Forces (resisting movement) and all the Tangential Forces (producing movement along the circumference).

The force tending to prevent movement is S N tanf + Lc. This is the total shear strength of the material along the arc of the circumference of the circle.

So, S **N Forces** = S N components X width of the slice X Unit weight of slope forming material X tanf (f = angle of internal friction) + Arc length (L) X Cohesion(c).

S T Forces = S T components (note the –ve sign) X width of the slice X unit weight of the slope forming material.

Now, **Factor Of Safety (FS)**= $\frac{\text{SN forces}}{\text{FT forces}}$

An example has been given in the Fig-2. The circle drawn following this procedure may not be the most dangerous circle along which the slide may recur. Hence, a few more trial circles should be analyzed and the one showing the lowest factor of safety should be considered.

For the centre of additional trial circles through the toe of the slide/slope, back up the line OD in Fig-1b and then up and away from it in a perpendicular direction in such a way that Od_1 is not greater than 1/2 OD and O_1d_1 is equal to 1/3 Od_1. O_1 will be the centre of a new trial dangerous circle with radius R_1 This new circle is analyzed as before and its factor of safety determined. The procedure is continued until the circle is found which gives the lowest factor of safety (FS). If the FS of a slope is known, the Geotechnical Engineer can check whether the desired FS incorporated in the design has been obtained after implementation of the suggested remedial measures. Similarly the most dangerous circle defines the limit up to which

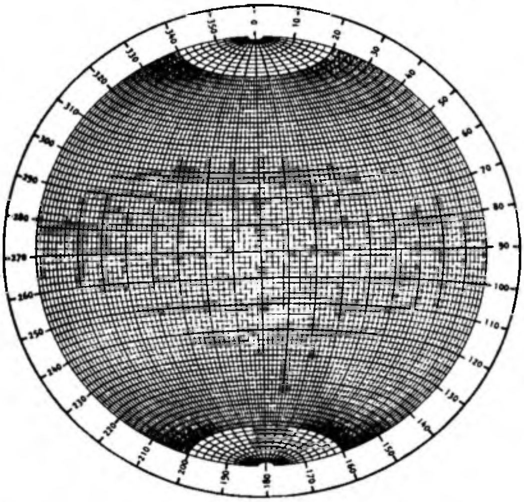


Fig. 2a: Equatorial equal-area stereonet marked in 2° intervals.

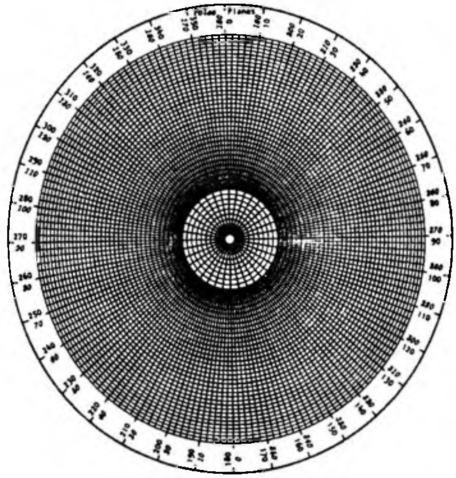


Fig. 2a: Polar equal-area stereonet marked in 2° intervals.

the slope forming material is likely to be involved in further sliding. It also helps to design the length of perforated pipes to be provided as subsurface horizontal drainage or depth of piles, if suggested to stabilise the slide.

It is well known that pore water pressure plays an important role in inducing slope instability. If there is seepage on the slide surfaces or there is a source of water above the slide in the form of reservoir/spring etc. The following formula may be used for calculation of factor of safety (FOS).

where, m = Pore pressure = $Zg_w \, Cos^2 b$

Z = Depth of slide i.e. Height of each slice

g_w = Density of Water (=1)

b = Slope angle

q = Angle between tangent and horizontal of each slice.

The data may be presented in a Tabular Form as follows:-

It may be mentioned here that drawing of slip circle by using this methodology is applicable for homogeneous/isotropic type of materials. But, in nature, the strata are rarely homogeneous. Hence, the slip plane may not be exactly circular. However, it gives a tentative idea about the depth of failure plane. In case of translational movement, the stability analysis procedure is almost same, only the slip circle is not required to be drawn.

The stability analysis following Swedish Slip Circle method(Bishop, Fellenius, Taylor etc.) is a tedious procedure as a number of slip circles are to be drawn and stability analysis is to be performed till the circle showing the lowest Factor of Safety is determined. But numbers of software (Slope/W, Seep/W etc,) are now available in the market. These can be used to get the result quickly.

Site specific study of rock slide

The rock slide may be mainly classified into three types (i) Planner failure (ii) Wedge

Slice No.	Height of a slice in meter	Area = Height x Width of a slice in m^2	Weight = Area x density at OMC	W Cos θ_1 (N-component)	W Sin θ_1 (T-component)	L (Arc length in meter)	μ gm/cm^2	Cohesion C kg/cm^2
1	2	3	4	5	6	7	8	9

failure and (iii) Toppling failure. Besides, there is another variety called Rock fall. The technique of study of rock slides is entirely different from that of a overburden slide. In case of Rock Slide the relation between the slope attitude and the attitude of the planner structures traversing the rocks dictates the stability status of the slope.

Desktop Work: The Desktop work is more or less similar to that of an overburden slide. Hence, it is not repeated in this context.

Field Investigation

- **Detailed Geological Mapping**

All the features mentioned under the subheads of the detailed geological mapping of the overburden slide are to be recorded except **iv, vi, ix and xi.** In case of rock slide emphasis is laid on the recording of rock types and their mode of occurrence, state of weathering of rock mass, all the planar structures like bedding, foliation, numbers of sets of joint/fracture and their attitudes, spacings, openings, degree of smoothness/ roughness, weathering/alteration, etc., Besides, tectonite fabrics like plunge of fold axis , attitude of axial plane of folds, style and number of generation/phase of folds, number of sets of shear zones, fault zones with their attitude, continuity, width of crushed/pulverized zones or gougy zones etc. should be recorded. If rocks are appreciably weathered, the procedure of data collection is similar to that of overburden slide. But sometimes it becomes deceptive to recognize whether it is a rock or overburden slide as both rocks and debris are evenly distributed on the slide face. A close examination of this kind of slide will indicate whether rock got exposed due to overburden slide or rockslide removed the top overburden. It is suggested that both Q-Value (Barton, et el. 1974; Grimstad and Barton, 1993) and RMR of Bienawski (1989) of the rockmass should be determined. The main advantage of these two rating schemes is that an approximate Uniaxial Compressive Strength from the Q value and approximate Cohesion and Angle of Internal Friction from the RMR can be determined in absence of core samples from borehole. In absence of core samples, Uniaxial Compressive Strength is generally computed fro the Point Load Index value but it may not be a reliable value as point load index is determined from a piece of rock sample. It may not represent the value of rockmass. Hence, it is suggested that the Uniaxial Compressive Strength determined from the Q-value of Barton should be compared with the value determined from the point load index and an acceptable value should be considered.

It is absolutely necessary to delineate the type of failure like planar, wedge or toppling failures as the direction, length, spacing of rock bolts, a vital rock supporting device, are decided depending on the shape, size and direction of (wedges/planes) failure. Sometimes rocks are traversed by number of planar structures. Only seeing the slide it is not possible to delineate the most vulnerable planar structure or wedge on a slope susceptible to sliding. It can be easily worked out by plotting on an Equatorial Net (Fig.2a and 2b)). A plane can be plotted on a great circle (Fig.2a & 3) and alternatively the pole of this plane can be plotted (Fig.2b & 3). Procedure of representation of Circular

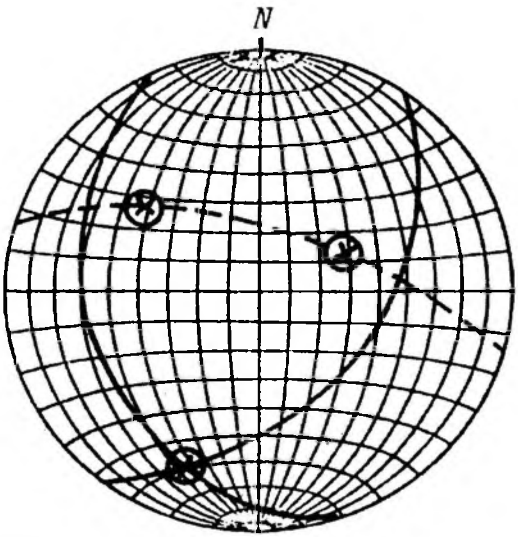
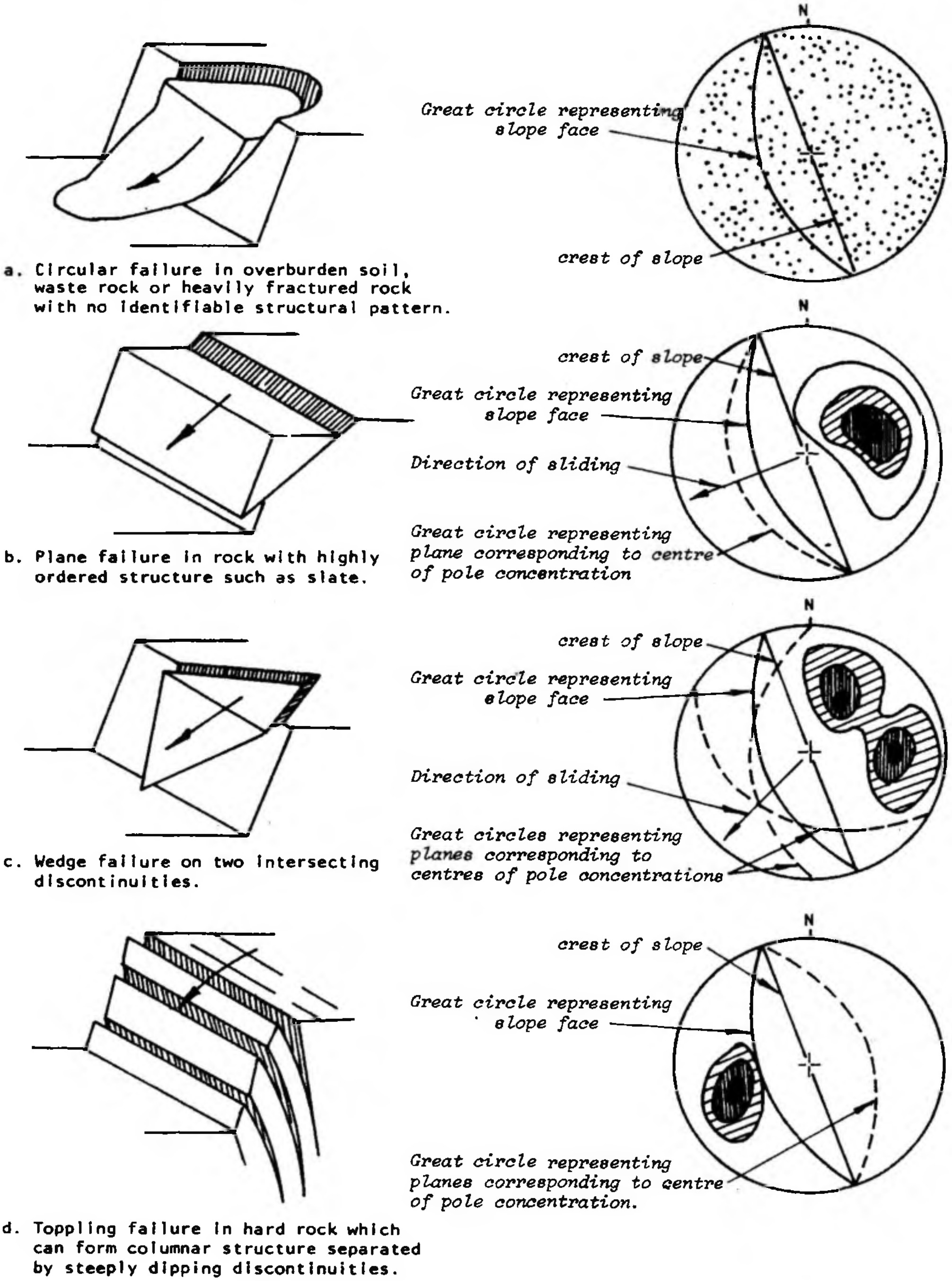


Fig. 3



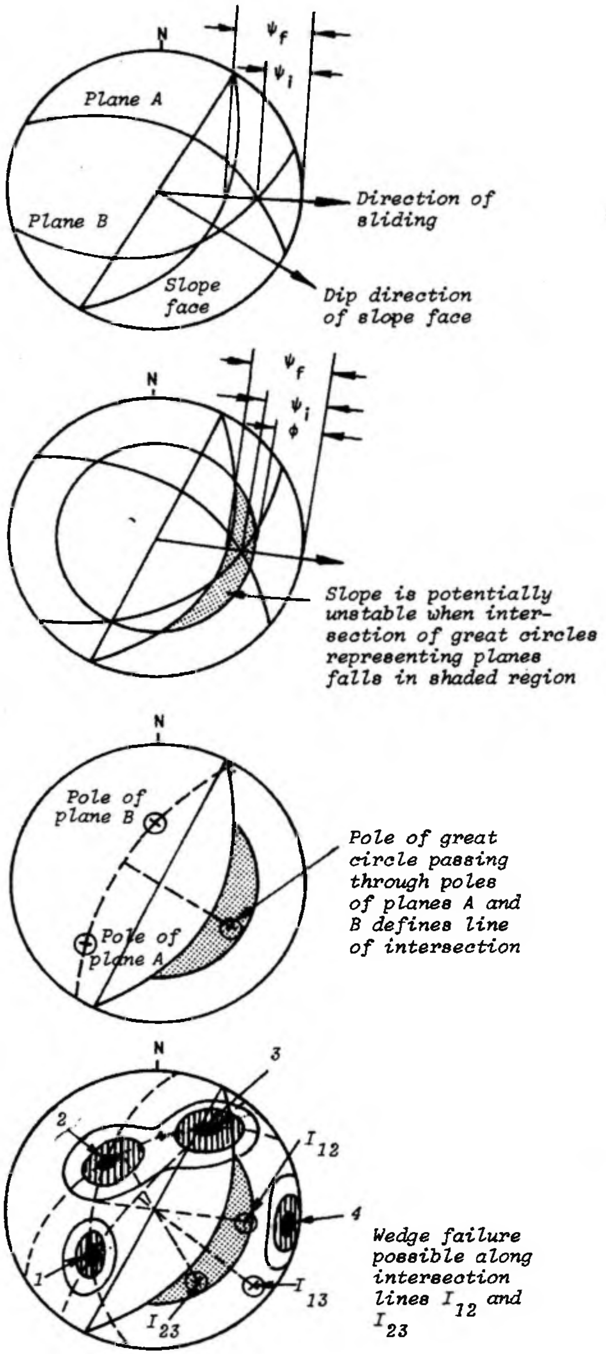
a. Circular failure in overburden soil, waste rock or heavily fractured rock with no identifiable structural pattern.

b. Plane failure in rock with highly ordered structure such as slate.

c. Wedge failure on two intersecting discontinuities.

d. Toppling failure in hard rock which can form columnar structure separated by steeply dipping discontinuities.

Fig. 4: Main types of slope failure and stereoplots of structural conditions likely to give rise to these failures.



a: Sliding along the line of intersection of planes A and B is possible when the plunge of this line is less than the dip of the slope face, measured in the direction of sliding, ie

$$\psi_f > \psi_i$$

b : Sliding is assumed to occur when the plunge of the line of intersection exceeds the angle of friction, ie

$$\psi_f > \psi_i > \phi$$

c : Representation of planes by their poles and determination of the line of intersection of the planes by the pole of the great circle which passes through their poles.

d : Preliminary evaluation of the stability of a 50° slope in a rock mass with 4 sets of structural discontinuities.

Fig. 5

Table II: Values of adjustment factors for different joint wedge orientations

Case of slope failure		Very favourable	Favourable	Fair	Unfavourable	Very Unfavourable
P	$\alpha_j - \alpha_s$	>30°	30° - 20°	20° - 10°	10° - 5°	<50°
T	$\alpha_j - \alpha_s - 180°$					
N	$\alpha_i - \alpha_s$					
P/W/T	F_1	0.15	0.40	0.70	0.85	1.00
P	β_j	<20°	20° - 30°	30° - 35°	35° - 45°	>45°
W	β_i					
P/W	F_2	0.15	0.40	0.70	0.85	1.00
T	F_2	1	1	1	1	1
P	$\beta_i - \beta_s$	>10°	10°-0°	0°	0° - (-10°)	<-10°
T	$\beta_j + \beta_s$	<110°	110°-120°	>120°	--	--
P/W/T	F_3	0	-6	-25	-50	-60

failure in overburden soil, waste rock or heavily fractured rock with no identifiable definite structural pattern has been shown. In the Fig.4b, c & d and Fig 5a, b, c & d the procedure of representing planar, wedge and toppling failure on the equatorial net has been shown. It is a simple procedure (Hoek & Bray'1977). Plot the slope, all the planar structures and angle of internal friction of the rockmass (approximately determined from RMR or by Triaxial shear test). Now identify the most vulnerable plane or wedge susceptible to sliding with respect to the slope Fig.4b, c & d and Fig 5a, b, c & d. Sometimes poles of the great circles representing the planar structures are plotted. A few software are available in the market (e.g. Unwedge) for rock wedge analysis. It may be mentioned here that there may be multiple types of failure in different parts of a rock slide. Depending on the type of failure the corrective measures are suggested.

Of late Romana (1985) has proposed a slope stability classification system for assessing the degree of instability of rock slope, called SLOPE MASS RATING (SMR) which is obtained from adjustment factors of the planar structures Bieniawski's (1979,1989) ROCK MASS RATING (Annexure-I) (RMR) by subtracting wedge – slope relationship and adding a factor depending on method of excavation.

SMR = RMR basic – $(F_1.F_2.F_3) + F_4$....Eq (i)

F_1 depends upon parallelism between dip direction of the planar structure /plunge direction of a wedge and dip direction of slope face. It ranges between 0.15 and 1. If the angle between dip direction of a critical planar structure/plunge direction of a wedge and dip direction of the slope face is >30°, its value is 0.15, indicating low probability of failure. Its value is '1' when both are near parallel and probability of failure is very high.

The value of F_1 was initially established empirically but subsequently it was found to match approximately the following relationship:

Table III: Values for adjustment factor f_4 for method of excavation

Method of Excavation	F_4 value
Natural slope	+15
Pre-splitting	+10
Smooth Blasting	+8
Normal blasting or Mechanical excavation	0
Poor blasting/Deficit blasting	-8

$F_1 = (1 - \text{Sin } A)^2$

Where, A = Angle between the dip direction of slope face (a_s) and that of planar structure (a_j) /plunge direction of line of intersection

SMR Value	Support System
1. 65 – 100	None, Scaling
2. 30 – 75	Bolting, Anchoring
3. 20 – 60	Shotcreting, Concreting
4. 10 – 30	Wall erection, Re-excavation.

(a_i) i.e. (a_s - a_j or a_i).

F_2 = Dip of planar structure (b_j) or plunge of wedge (b_i) in the Planar mode. Its value range between 0.15 and1.

It is 0.15 when the dip of the critical planar structure (b_j) /plunge of wedge (b_i) is <20° and '1' for dip of planar structure plunge of wedge >45°. For toppling mode of failure F_2 remains equal to '1'.

F_2 = tan b_j /b_i.

F_3 = Relationship between the dip of slope face and dip of a critical planar structure/ plunge of a wedge. In planar failure, F_3 refers to a probability of a planar structure/wedge daylighting on the slope face.

F_3 = 0 to 60. Conditions are called fair the slope face and dip of a critical planar structure/plunge of a wedge is parallel.

F_3 (Unfavorable) for planar/wedge failure=slope dips 10° more than dip of a critical planar structure plunge of a wedge.

F_3 (Unfavorable for toppling failure) = b_j/ b_i+b_s>120°)

The minimum and maximum SMR values calculated by the Equation - (i) are 0 and 100 respectively. Romana (1985) defined the following five stability classes: -

In a broader sense, the SMR ranges for each group of support measures are as follows: -

Remedial Measure

Overburden Slide

Water is almost always an agent contributing

Table IV: SMR classes

Class No.	V	IV	III	II	I
SMR value	0-20	21-40	41-60	61-80	81-100
Rock Mass Description	Very bad	Bad	Normal	Good	Very good
Stability	Completely Unstable	Unstable	Partially Stable	Stable	Completely Stable
Failures	Big planar or soil like or circular	Planar or big wedges	Planar along some planar structure and many wedges	Some block failure	No failure
Probability of Failure	0.9	0.6	0.4	0.2	0

Table V: Suggested support for various smr classes

SMR Classes	SMR Values	Suggested Supports
Ia	91-100	None.
Ib	81-90	None, scaling required.
IIa	71-80	(None, toe ditch or fence), spot bolting.
IIb	61-70	(Toe ditch or fence nets), spot or systematic bolting.
IIIa	51-60	(Toe ditch and/or nets), spot or systematic bolting, spot shotcrete.
IIIb	41-50	(Toe ditch and/or nets), systematic bolting/anchors, systematic shotcrete, toe wall and/or dental concrete.
IVa	31-40	Anchors, systematic shotcrete, toe wall and or concrete (or re-excavation), drainage.
IVb	21-30	Systematic reinforced shotcrete, toe wall and/or concrete, re-excavation, deep drainage.
Va	11-20	Gravity or anchored wall, re-excavation.

i) Treatment of slide material:	a) Unloading from the crown of slide
	b) Loading of toe
	c) Protection against toe erosion by boulder crate in wiremesh, gabion wall etc.
	d) Development of benches with safe slope (determined from stability analysis) at suitable levels on the slide face.
ii) Surface drainage control:	a) Lined catch water drain above the crown of the slide/lined contour drain on the benches/cascading chute drain/toe drain
	b) Lining of the existing nala draining the slope
	c) Disposal of water from the slope into a natural drainage away from the affected slope
	d) Lined drainage network for disposal of wastewater from the slope for preventing percolation into the distressed slope.
iii) Subsurface drainage:	a) Horizontal drain at different levels with perforated pipes surrounded by filter
	b) Drainage galleries
	c) Well system/sand drains
iv) Retaining structure:	a) Low and high concrete walls
	b) Concrete crib walls
	c) Stone masonry
	d) Stone crates
v) Driving of piles :	Depending on the magnitude of the problem
vi) Vegetation cover :	Very effective measure. Plants with large consumption of ground water and high transpiration are most suitable like poplar, willows, birches
vii) Use of geogrids/geotextile/ geomembrane	Most effective for soil covered slope
viii) Soil nailing	Most effective for soil covered slope
Rock slide	
i) Shotcreting with wiremesh or Steel Fibre Shotcrete(SFR)	Jointed and partially weathered rocks
ii) Rock Bolts	Most effective for widely spaced, jointed rock.

to the failure of natural earth slopes. Drainage is without question the most generally appreciable corrective treatment for slides. It is often the only economic choice for the treatment of very large slides or flows. However, on the basis of the site condition the following corrective measures are generally adopted.

● Landslide inventory

Landslide Inventory is the documentation of all the landslides all over the country with some preliminary information like location, dimension of the slide, date of initiation, rain/ earthquake induced, recurring type or not, rockslide/overburden slide, planar/wedge/ toppling failure in case of rockslide, rotational/ transitional failure, single/multiple rotation in case of overburden slide, rock types/ composition of overburden, rainfall record on the date of initiation or earlier two-three days, if available, devastation caused/likely to be caused, elements at risk, degree of risk, approximate runout distance, approximate cause/causes of the slide. The main purpose of this study is not only to prepare a Landslide Archive of the country but also to identify the priority areas / conspicuous, recurring or fresh slides posing high risk requiring immediate investigation by LHZ or Site Specific Study respectively. But there are some unavoidable problems in data collection. Sometimes the exact date of occurrence of a landslide, rainfall data on the date of the event are not available rendering it difficult to make any prediction about the return period of a landslide and to establish a tentative threshold value correlating the amount of rainfall with the time of initiation of the mobilization event.

Generally, Landslide Inventory is done utilizing high resolution cartosat imageries or large scale aerial photographs followed by field checks. GSI is at present carrying out LHZ along important road corridors and river basins on Macro scale. In course of this study Landslide Inventory is also being done every year. Besides, data are also collected from the GSI's old reports which do not fetch all the required information Moreover in recent years the numbers of incidences of landslides have increased alarmingly. Hence, a programme of updating the Inventory data has been taken up as a continuous process which will be immensely helpful in the development of Landslide Inventory Archive of our country.

Landslide hazard zonation

The main purpose of Landslide Hazard Zonation (LHZ) is to divide the landslide prone hilly terrain into different zones according to their relative degree of slope instability for perspective project planning by the user agencies. Generally the scale of mapping is selected on the basis of nature of requirements. In order to bring uniformity in the scale of mapping all over the country, the following proposal has been made in the recently prepared document on "National Disaster Management Guidelines on Landslide" by the National Disaster Management Authority, an Apex Body under the chairmanship of Honb'le PrimeMinister of India, constituted in 2004 by the Government of India :

- LHZ on Macro scale : 1: 50,000/25,000
- LHZ on Meso scale : 1: 10,000/5000
- Any other studies on larger than 1:5000 scale should be called Site Specific Study of Landslide.

The philosophy behind this classification is that LHZ divides the landslide prone hilly terrain into different zones according to their degree of susceptibility to landslide. On the basis of observations made during carrying out investigation of different types of landslides in varied gemorphic and geological settings, some causative factors or geoenvironmental parameters like, slope morphometry, lithology, structure, relative relief, landuse, landcover, hydrogeology, erosional condition of slope, shear strength of slope forming materials and three important triggering agents like rainfall, seismicity and anthropogenic interference have been identified responsible for inducing slope instability.

At present, Geological Survey of India is carrying out LHZ on both Macro and Meso scales following modified BIS Guidelines on Macro scale. A very important parameter shear strength of slope forming materials has been taken into consideration for LHZ on Meso scale. It is a readily applicable rating scheme based on the superimposition technique. Some ratings have been assigned to these causative factors as per their relative importance inducing slope instability. The basic unit of this type of mapping is a Facet which encompasses some polygonal area on the Toposheet having uniform slope inclination and direction. This facet map is superimposed on each thematic map and total rating of each facet is calculated. On the basis of Total Estimated Hazard Value of each facet, different zones showing different degree of slope instability are demarcated. Finally, LHZ Map is validated with the Landslide Incidence Map to test the accuracy of the procedure of mapping. But, there are different methodologies of LHZ mapping recently in practice in our country. These are Artificial Neural Network (ANN), Fuzzy Set Theory, The basic difference between the BIS methodology and other methodologies is that the former does not consider landslide incidence while landslide incidence is taken into consideration in the latter methodologies. GSI is following the modified BIS methodology because of its simplicity and the speed of application facilitating huge area coverage within a short span of time with high accuracy.

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