Hazard evaluation and risk assessment of reservoir rim slopes - a case study

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Abstract

This paper briefly describes the guidelines of landslide hazard evaluation suggested by BIS and GSI and a risk assessment approach developed further to the suggested guidelines. As a case study the landslide hazard of vulnerable slopes of a reservoir rim is evaluated by using suggested guidelines and risk assessment approach. The total risk of landslide impact is used to optimized and prioritized slope stabilization measures to control the landslide.

Keywords: Landslides, Reservoir, Hazard zonation, Risk assessment, Impact factors.

1. Introduction:

Landslides are one of the main Natural Hazards causing enormous loss to life and property in the hilly terrain of our country invariably every year during the Monsoon period or in the event of Earthquake. It has been reported that about 15% land area i.e. about 0.49 million km^2 land of our country covering the entire Himalayan Mountain Chain, Northeastern parts, parts of the Eastern Ghats and the Western Ghats and Nilgiri Hills in the southern parts of our country is highly susceptible to landslide.

The mountainous terrains such as Himalaya are typically composed of steep slopes, high relative relief, weathered, fractured and folded rocks with unfavorable hydro geological conditions. One or more these factors are sometime responsible for the triggering of landslides. Moreover, the implementation of development schemes like roads, dams, building construction, etc., often causes significant environmental damages making the situation more unfavorable for landslides to occur.

Therefore, scientific evaluation of the landslide hazard potential of a terrain is essential to categorize the domain in terms of its magnitude. The Bureau of Indian standard has laid down some guidelines for preparing the Landslide Hazard Zonation (LHZ) Maps for this categorization at various levels of scale, as in [1]. However, the landslide potential being zoned on the regional map using the standard procedure, the risk associated with the various zones of landslide has not been accounted for. As the risk associated with a low potential slide may be high due to its impact on the surroundings, and vice-versa. In absence of such valuable information the anticipated landslide mitigation measures ends up to be uneconomical and are often postponed or even dropped due to lack of funds and operational issues to execute these measures in difficult terrains.

Geological Survey of India has developed a standard operating procedure for landslide investigation to account for this gap as in [2]. The procedure in addition to the landslide hazard zonation introduces a site specific study of Landslide based on type, nature and stability of the slides. Development of an inventory of the landslides across the nation is also addressed by GSI on macro level based on maximum information on the slide characteristics and the elements at risk. The document certainly gives some hope in the direction of optimizing the landslide mitigation measures if practiced faithfully but the concept of a site specific numerical approach still remains unaddressed.

Therefore, the void in hazard evaluation and risk assessment methods requires the development of an innovative quantitative study carried out at potential landslide zones based on some impact oriented factors. The impact factors need to be evaluated based on respective analytical studies applicable to the specific site or the project. An example of a landslide posing high risk to the local habitants is shown in Photograph 1.

Photograph 1 A landslide after occurance

The case study presented in this paper is a part of a consultancy assignment of a reservoir rim stability study conducted for a hydroelectric project in J & K. In this case study landslide hazard zonation mapping of the reservoir rim area has been done on a macro scale to identify the landslide vulnerable locations and its potential. Further a risk assessment study is carried out based on the concept of risk in terms of impact of potential landslide on the site. Based on the risk analysis the landslide mitigation measures were optimized.

2. Project Description:

The hydroelectric project with an installed capacity of about 850 MW is located in J & K and is presently under construction stage. The project envisages development of a water storage reservoir extended up to 14 km in upstream. The reservoir is associated with the formation of rim composed of natural slopes of varying gradient, land use and material.

The objective of the project was to study and analyze the stability of the natural slope when subjected to the impoundment of the reservoir.

The natural overburden slopes of the reservoir rim are also endangered by the landslides of varying size and scale depending upon the geology and geomorphology of the strata. A massive slide involving the movement of huge mass into the reservoir may be hazardous in terms of loss of storage capacity and formation of secondary waves overtopping Dam structure. The loss of life and property due to habitation and infrastructure existing within the influence zone of landslide is equally significant if not less.

The waves formed due to massive slides at high velocities may be catastrophic to the local inhabitants adjacent to the reservoir and the dam structure itself as shown in Photograph 2. The tendency of secondary waves to travel downstream is responsible for the impact it will make on the dam structure in terms of both impulse forces and discharge by overtopping the dam crest. Therefore, the study of such a phenomenon is imperative to evaluate the risk involved and take necessary measures to reduce it.

The vulnerable locations identified in macro level landslide hazard zonation mapping were studied to evaluate the risk of impact made by the slides on various factors like stability, habitation, impact on dam and local infrastructure in the influence zone of landslide.

Photograph 2 Typical landslide in a reservoir rim

3. Landslide hazard zonation:

The guidelines of landslide hazard evaluation and generation of landslide hazard zonation maps presented in GSI procedures on Macro and Meso scale are suggested based on similar concept as provided in the Indian standard with some additional site specific studies.

Indian standard suggests dividing the land surface into zones of varying degrees of stability in a particular scale based on the estimated significance of causative factors in inducing instability. Multi-purpose terrain evaluation maps generated by landslide hazard zonation may be used as a basis of preliminary planning of the development schemes. It will help to select geo-environmentally sound sites which may pose minimum hazards of instability.

Macro level landslide hazard evaluation and zonation mapping are carried out on a scale of the order of 1:25 000 or 1:50000. The primary factors for macro-zonation of landslides are suggested by the standards as major factors of the instability caused by lithology, structure, slope morphometry, relative relief, land use-land cover, and hydrogeological conditions. The area to be zoned for landslide hazard is divided into small zones called facets having identical slope character in terms of direction and inclination of slope. The identified facets are generally delimited by ridges, spurs, gullies, rivers and roads etc.

The procedure suggested by Indian standard for landslide hazard evaluation and zonation mapping on macro level are described briefly in this paper in subsequent sections.

4. Landslide hazard evaluation scheme:

The landslide hazard evaluation scheme is a numerical rating system based on the major causative factors mentioned above. The individual maximum landslide hazard evaluation ratings (LHEF) for different causative factors are determined on the basis of their estimated significance in causing instability as presented in Table 1. The higher the rating more is the tendency of the factor to cause slides.

Table 1
Maximum LHEF rating for different causative factors for micro – zonations

S. no.	Causative Factor	Maximum LHEF Rating
1	Lithology	2
2	structure	2
3	Slope morphometry	2
4	Relative relief	1
5	Land use and land cover	2
6	Hydrogeological condition	1

The maximum ratings presented above are estimated by the summation of individual sub ratings associated with respective sub factors and categories of each causative factor. Various categories of the causative factors are described as under,

A. *Lithology*

The lithology of the facet may be composed of rock as well as soil overburden and the categories are decided accordingly. The response of rocks to the processes of weathering and erosion is suggested to be the main criteria in awarding the ratings for the sub-categories of rock lithology. A correction factor on the status of weathering of rocks shall also be incorporated.

In case of slope composed of soil materials the origin and age are suggested to be the main considerations in awarding the ratings. The older alluvium is generally well compacted having high strength whereas slide debris are generally loose and have low shearing resistance and erosion resistance.

B. *Structure*

Structural features in case of jointed bed rocks are considered as exclusive causative factors in the suggested guidelines. It includes primary and secondary discontinuities in the rocks such as bedding planes, joints, foliations, faults and thrusts. The discontinuities in relation to the slope inclination direction have more influence on the stability of slopes, devised under various angular situations listed as under.

- The degree of parallelism between directions of discontinuity or the line of intersection of two discontinuities and the slope.
- The amount of the dip of discontinuity or plunge of the line of intersection of two discontinuities.
- The difference in the dip of discontinuity or plunge of the line of intersection of two discontinuities with the inclination of the slope.

The LHEF rating factor is determined adding sub ratings of above three situations are categorized in terms of favorability represented by respective ranges of angles. In case of soil, the depth of cover shall be considered for awarding the ratings.

C. *Slope Morphometry*

Slope morphometry factor is defined by the slope categories on the basis of frequency of occurrence of particular inclinations on the slope. Five categories representing the inclination of slopes are suggested as escarpment or cliff, steep slope, moderately steep slope, gentle slope and very gentle slope having different angular ranges and individual ratings. The most appropriate category applicable to the slope facet is assigned to it along with its rating.

D. *Relative Relief*

The relative relief factor of a slope facet represents the local relief of maximum height between the ridge top to the valley floor measured in the direction of slope. The hazard evaluation rating for this causative factor can be selected from three categories of slopes identified as low, medium and high with specific range of heights.

E. *Land Use and Land Cover*

The nature of land cover is suggested to be an indirect indication of hill slopes stability. In general forest cover protects the slope from the effects of weathering and erosion. A well spread root system increases the shearing resistance of the slope material. However, barren and sparsely vegetated areas show faster erosion and greater instability.

The agricultural lands being relatively flatter and represent areas of repeated artificial water charging for cultivation purpose may be considered stable. Therefore, the rating is suggested to be awarded primarily based on the criteria of cover intensity divided in five different categories. It is also suggested that in thickly populated areas, smaller facets shall be taken to get a better distribution of rating.

F. Hydrogeological Conditions

It is established fact that the groundwater in hilly terrain is generally channelized along structural discontinuities of rocks, it seldom attains a uniform flow pattern. As the observational evaluation of the groundwater on hill slopes is not possible over large areas, therefore for purposes of quick appraisal the nature of surface Indications of water categorized as dry, damp, wet, dripping and flowing conditions are suggested to be used for assigning of the rating. It is also suggested that the hydro geological appraisal shall be carried out soon after the monsoon season as the slopes with self-draining materials are likely to become dry.

Additionally a 100m to 200m strip on either side of major faults, thrusts and intra thrust zones shall be awarded an extra rating of 1.0 to consider higher landslide vulnerability depending upon intensity of fracturing.

5. Total estimated hazard (TEHD) evaluation:

The total estimated hazard (TEHD) is a representation of the net probabilities of slope instability and suggested to be calculated facet-wise. The TEHD of each and every facet is obtained by adding the ratings of the individual causative factors obtained from LHEF rating scheme. All facets in the area are designated by a zoning of landslide hazard based on the associated range of TEHD described in Table 2.

Table 2
Landslide hazard zonation based on TEHD

Zone	TEHD Value	Description of Zone
I	< 3.5	Very low hazard (VLH) zone
II	3.5 to 5.0	Low hazard (LH) zone
III	5.1 to 6.0	Moderate hazard (MH) zone
IV	6.1 to 7.5	High hazard (HH) zone
V	> 7.5	Very high hazard (VHH) zone

6. Macro zonation LHZ mapping:

The macro level LHZ mapping of an area is an approach to visualize the probabilities of landslide hazards of an area preferably on scales 1: 25000 or 50000. The LHZ mapping is suggested to be comprised of mainly desk study and field investigations.

The desk study broadly consists of identifying the important parameters with the help of aerial photographs, satellite imageries and topo-sheets. Various types of pre-field maps are generated on 1: 50000 scale, based on causative factors such as lithological map, structural map, slope morphometry map, relative relief map, rock outcrop and soil cover map, land use-land cover map and a hydrogeological map. These are also called as terrain evaluation maps.

The information collected from the desk study helps to plan and execute a systematic field investigation for a detailed lithological and structural mapping. The details of other maps prepared during the desk study could be verified in the field and modified wherever necessary. The data collected during field study is used for estimating the total hazard of the facets as explained in previous section.

A macro-zonation LHZ map is finally generated based on the facet-wise distribution of TEHD values.

7. Interpretation of macrozonation LHZ map:

The VLH and LH zones are generally safer for development schemes. The MH zones are suspected to contain some local pockets of unstable slopes. Detailed geotechnical investigations are suggested to be carried out to identify these pockets so as to adopt proper remedial measures. The HH and VHH zones typically consist of unstable slopes, which may be active. Detailed geotechnical appraisals of unstable slope shall be carried out by mapping the slopes on 1:1 000 or 1: 2 000 scales in order to evaluate the nature of instabilities, so that proper precautionary measures could be adopted during construction as well as for evolving appropriate mitigation measures to protect the stability of the area. It is also suggested that the risk to existing civil engineering structures shall be assessed on the basis of hazard rating, expected modes of slope failure and type of damage to life and properties.

The LHZ maps are suggested to be revised from time to time specially after every major earthquake (>5 on Richter's Scale), major flood, cyclone, developmental activity, mining, cloud burst and new landslides events.

8. Site specific study of landslide:

Supplementing the guidelines of BIS as described in previous sections a standard operating procedure is outlined by GSI as in [2] suggesting that site specific study shall be carried out for slopes having landslide hazard potential. Most important aspect of this study is stability analysis of the slope. The slopes for stability analysis are broadly classified in soil/overburden and rock slopes. The major aspects suggested for site specific studies of slides are described as under:

G. *Investigations*

Detailed investigations are suggested for both the categories of slides, i.e. soil slides and rock slides, respectively. It is suggested to collect useful data from field as well as lab testing on representative samples.

H. *Stability Analyses*

The slopes possessing landslide hazard are analyzed for stability using appropriate methods of analysis for soil/overburden and rock slopes, respectively as briefed under,

- For soil or overburden slopes the slip circle method of stability analysis is adopted as the most likely mode of failure shall be a circular slide. The Swedish slip circle methods as established in [3] and [4] incorporates drawing of multiple probable circles along which the slope is likely to fail. The circle is divided into several slices transferring forces on its sides as well as failure surface based on the assumptions made by different researchers. A factor of safety (FOS) is determined for each circle as the ratio of resisting forces to the driving forces along the failure circle. The slip circle with minimum FOS is discovered by multiple trials and its FOS is reported as the measure of slope instability.

- Basically the rock slides are categorized in three types, i.e. Planar failure, Wedge Failure and Toppling Failure on the basis of the mode of failure generally associated with rock slopes. The rock slope stability analysis is generally carried out by spherical projection method using equal area net proposed in [5]. The concept generally known as Day lighted Envelope considers that the slope is likely to fail if the dip of a planar structure like bedding, foliation, joint, fracture, shears zone, minor fault plane etc. or plunge of a wedge is less than the dip of the slope as the planar structure or the wedge, respectively. A slope classification system known as Slope Mass Rating (SMR) for assessing the degree of instability of rock is also proposed in [6] which involve subtracting the adjustment factors from Rock Mass Rating (RMR) developed as in [7] based on the joint-slope relationship and method of excavation. Five classes of SMR are established for respective range of ratings in terms of type of rock mass, stability, failure mode and probability of failure. Various support measures are also suggested for different ranges of SMR accordingly. It is also suggested to use numerical softwares for rock wedge stability analysis.

I. *Remedial Measures*

- For Overburden Slides the major treatment measures that are suggested to be adopted based on site specific conditions are loading and unloading at toe and crown of the slope respectively, cutting and benching of slope profile, surface and subsurface drainage control, Retaining structure, Driving of piles, Vegetation cover, Use of Geogrids/Geotextile/Geomembrane etc. and Soil nailing.

- In case of rock slides shotcreting with wire mesh or Steel fibre shotcrete is suggested for jointed and partially weathered rocks as per the design. However, Rock Bolts are considered as most effective measure for widely spaced jointed rock mass.

9. Inventory of landslides:

It is stated that an initiative has been taken by GSI to make an archive of all identified landslides in the country covering the landslide-prone hilly terrain. Landslide incidence maps are prepared preferably on 1:50000/25000/10000 scale from the study of available aerial photographs and Landsat imageries from past. After that field checks are carried out for collecting maximum available information for each slide like location of the slide, Type and size of slide, mode of failure, age of slide, past three day history of rainfall and earthquake, approximate run out distance, nature and extent of damages caused, further sliding possibility, any local activity that could have triggered the slide and elements at risk due to the slide.

In addition to above it is also suggested to record different components of landslides as illustrated in Figure 1.

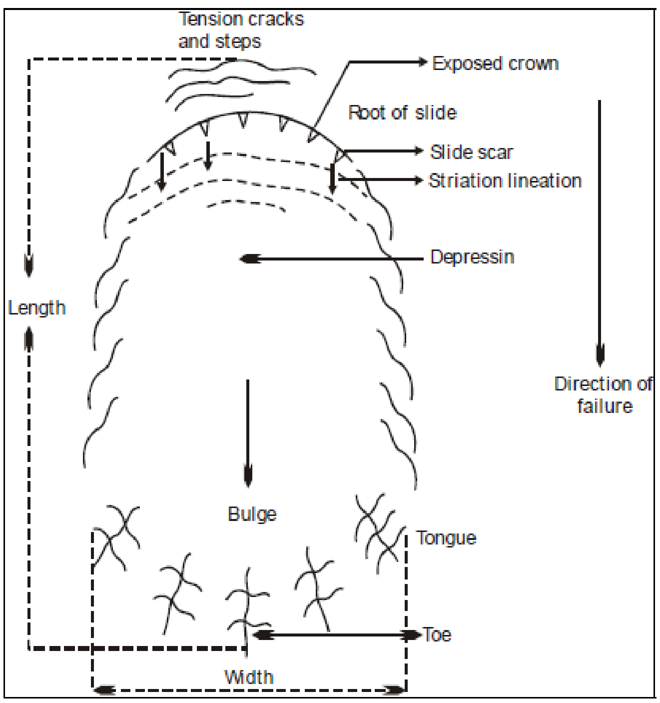

Figure 1 Different components of landslides to be mapped

Various symptoms that could be observed before a major landslide are also suggested in [2] listed as follows:

- Unexpected Springs, seeps, or saturated ground.
- New cracks or unusual budges in the ground, street pavements or sidewalks. Heaving of soil.

- Ancillary structures tilting and/or moving relatively.
- Tilting or cracking of concrete floors and foundations.
- Broken water lines and other underground utilities.
- Leaning telephone poles, trees, retaining walls or fences.
- Offset in fence lines.
- Sunken or down-dropped road benches.
- Sudden decrease in creek water levels though rain is still falling or just recently stopped.
- Sticking doors and windows, and visible open spaces indicating jambs and frames out of plumb.

10. Need of risk assessment:

Although the aspect of risk assessment has been addressed in the guidelines of Indian standard in terms of damage expected to the existing structures based on hazard ratings. However, the procedure to evaluate the same has not been elaborated.

The procedure suggested by GSI proposes the need of acceptable guidelines for landslide hazard and risk zonation stating the shortcomings of available BIS guidelines. The site specific study suggested by conducting investigations, stability analysis and selecting appropriate remedial measures to prevent potential slides can be applied effectively.

However, the categorization of area based on risk or danger to the local features is still not addressed to help streamline the implementation of selected remedial measures.

Therefore, there is an essential requirement to establish a systematic approach to evaluate the risk of slides in terms of suitable impact factors based on site specific features. The risk of impact of slides will certainly help in optimizing the relevant landslide remedial measures and prioritize the execution by focusing the high risk zones.

11. Risk assessment approach:

An attempt has been made to supplement the conceptions projected by BIS and GSI for risk assessment of landslide hazard zones. A semi quantitative approach is proposed in this paper based on site specific and impact oriented risk factors associated with the slopes having landslide hazard potential.

The landslide hazard evaluation as per the guidelines of BIS is imperative to identify the vulnerable slopes and quantify the hazard of slope, before risk assessment. The landslide hazard evaluation shall be carried out in micro scale (1: 2000) or macro scale (1: 25000), if budget is constrained.

To determine the risk of slide impact four risk factors are established to be evaluated in terms of stability of the slope and impact made by the probable slide on certain site specific elements. The factors chosen for the risk assessment proposed above are slope stability, local habitation, local infrastructure and a special impact factor applicable to the slide.

An appropriate risk rating on a scale of 0 to 5 is assigned to each factor based on the risk analysis and the total risk is evaluated by adding up all individual risk factors. Unlike the interpretation of hazard ratings based on causative factors higher the ratings of risk, lesser will be the damage. Based on the risk ratings five categories of individual and total risk are suggested. The risk factors selected are described as under,

Slope Stability

The stability analysis of the slopes shall be carried out in similar manner as suggested in the GSI procedures. The stability of vulnerable slopes shall be analyzed according to the theories applicable based on the composition of slope, i.e. Soil overburden and rock slopes.

The stability of soil overburden slopes is generally represented in terms of minimum factor of safety. However, the stability associated with rock slopes is characterized depending upon the analysis method. Generally rock stability is represented by minimum factor of safety in numerical methods and by ratings in classification methods, respectively. The analysis should be carried out considering worst possible slide under all applicable loading like seismic forces; traffic loads etc. and critical hydraulic conditions.

In case analysis resulting factor of safety the risk ratings are assigned to the slope based on the degree of its instability as suggested in Table 3.

Table 3
Slope stability risk rating

Minimum FOS	Rating range	Description of Risk
0.0 to 0.5	0.0 to 1.0	Maximum risk
0.6 to 1.0	1.1 to 2.0	High risk
1.1 to 1.5	2.1 to 3.0	Moderate risk
1.6 to 2.0	3.1 to 4.0	Low risk
2.1 and above	4.1 to 5.0	Minimum risk

In case analysis resulting ratings for a slope as a measure of instability like SMR having five categories, the risk rating is determined proportionally with the instability ratings.

Local habitation

The damage to the habitation over and around the vulnerable slopes which is supposed to get affected in case of slides shall be evaluated based on site specific observations. This damage is mainly estimated in terms of human life, agricultural value, environmental and social factors which are either lying in the zone of landslide or influenced due to movement of slided mass.

Based on the severity of damage to local habitation risk ratings are assigned out of the scale of 0 to 5 with five risk categories as suggested in Table 4.

Table 4
Local habitation risk rating

Damage	**Rating range**
Extreme damage	0.0 to 1.0
High damage	1.1 to 2.0
Moderate damage	2.1 to 3.0
Low damage	3.1 to 4.0
No damage	4.1 to 5.0

The severity of probable damage due to slide can be assessed based on field observations and interaction with the occupants. A statistical detailed approach can also be developed to award the ratings.

Local infrastructure

The infrastructure which is located on the hazardous slopes or in the influence zone of the slide and likely to get impaired due to occurrence of slides shall be taken into consideration while estimating the impact risk of slides. The elements which should be considered includes immovable structures like roadways, railway lines, bridges, culverts, tunnels, public buildings like markets, schools, hospitals, government offices, communication towers, electricity utility, defense installations and any other structure of importance etc.

Based on the degree of damage to local infrastructure, risk ratings are assigned out of the scale of 0 to 5 with five risk categories as suggested in Table 5.

Table 5
Local infrastructure risk rating

Damage	**Rating range**
Extreme damage	0.0 to 1.0
High damage	1.1 to 2.0
Moderate damage	2.1 to 3.0
Low damage	3.1 to 4.0
No damage	4.1 to 5.0

The degree of probable damage due to hazardous slides can be assessed based on study of landslide hazard zonation maps and field observations. A statistical detailed approach can also be developed to award the ratings.

Special Impact Factor

The major aspects of impact of a slide on the surroundings are covered in the factors described in previous sub sections. However, there may exist a unique feature associated with a particular slide or its influence zone which may be critically affected by the occurrence of slide. Therefore all such aspects shall be investigated by field observations and a suitable analysis shall be carried out to evaluate the effect of slide on it. The impact of slide in terms of this special factor can be a function of the stability of the slope or the volume of the mass associated with the slide. Some common special impact factors are listed as under,

- Landslides into reservoirs
- Landslides near proposed constructions
- Landslides changing groundwater level
- Landslides near strategic locations

Based on the severity of landslide impact on special features, the risk ratings are assigned out of the scale of 0 to 5 with five risk categories as suggested in Table 6.

Table 6
Local habitation risk rating

Impact	**Rating range**
Extreme impact	0.0 to 1.0
High impact	1.1 to 2.0
Moderate impact	2.1 to 3.0
Low impact	3.1 to 4.0
No impact	4.1 to 5.0

The severity of impact due to probable slide can be assessed based on the study of LHZ maps, specific field observations and a suitable analysis for the feature to evaluate the impact quantitatively.

Finally the total risk of landslide impact shall be determined by adding up all individual ratings and categorized as listed in Table 7.

Table 7
Total risk of landslide impact

Total Rating range	**Description of Risk**
0.0 to 5.0	Maximum risk
5.1 to 10.0	High risk
10.1 to 15.0	Moderate risk
15.1 to 20.0	Low risk
20.1 to 25.0	Minimum risk

12. Landslide study in reservoir rim:

The landslide hazard zonation and its risk assessment study as presented in this paper have been implemented on a consultancy project of reservoir rim stability study. Both the studies are described as follows,

Landslide Hazard Zonation

The landslide hazard zonation of the reservoir rim area has been carried out on macro scale as per the available guidelines of the BIS. The total estimated hazard (TEHD) has been estimated by dividing the total reservoir rim area into four major facets as presented in Table 8.

Table 8
Evaluation of TEHD for reservoir rim

BIS-14496-Part 2; Guidelines		**Individual ratings**			
Causative Factors	**Maximum Rating**	**Zone-1**	**Zone-2**	**Zone-3**	**Zone-4**
Lithology	2	0.4 x 2 = 0.8	1.625	1.2	2.0
Structure	2	0.4	0.85	1.2	0.65
Slope Morphometry	2	1.85	1.2	1.7	0.5
Relative Relief	1	0.6	0.6	0.6	0.3
Land use and land cover	2	1.5	1.2	0.6	2.0
Hydro geological condition	1	0.0	0.2	0.25	0.5
TEHD rating	**10**	**5.15**	**5.675**	**5.5**	**5.95**

The total estimated hazard rating for all the four zones obtained on macro scale is found to be similar in terms of total rating though varying individually. The range of TEHD obtained is 5.15 to 5.95 which fall under the category of moderate hazard considering landslide occurrence.

Landslide Risk Assessment

It is important to assess the risk associated with the impact of landslide. Therefore the risk assessment of reservoir rim is carried out for all zones being in similar category.

However, it is recommended to optimize the study by conducting LHZ on a smaller scale with large no. of facets. A finer distribution of hazard zones will be obtained and the risk assessment study can be optimized by ignoring the zones with low and very low total landslide hazard ratings.

The individual risk factors including slope stability, local habitation and local infrastructure were studied and analyzed using the applicable methods and field observations. A special factor has been considered as the impact of massive slide on reservoir. All the factors are described as under,

The vulnerable slopes in all four zones were identified and studied to evaluate the risk of impact in terms of the factors described as follows,

- The most critical slope is identified in each zone and investigated to collect geological and geotechnical information required for conducting suitable stability analysis. Most of the slopes were found to be composed of soil overburden and hence factor of safety analysis is carried out considering all possible modes of failure, hydraulic condition such as full reservoir, sudden drawdown and worst seismic loading combinations. The details of analysis are not presented in this paper. The minimum FOS for most vulnerable slope in each zone is obtained and appropriate ratings are assigned to the zones according to the proposed categories of risk rating.
- The ratings for the impact of slide on local habitation are also assigned after detailed field observation. The vulnerable slope with maximum local habitation within a zone is considered for assigning the ratings.
- The ratings for the impact of slide on local infrastructure are also assigned after detailed field observation. The vulnerable slope with most critical structural feature within a zone is considered for assigning the ratings. The existing road which is proposed to be converted into national highway is considered as major feature while assigning the ratings.
- The impact of landslide into the reservoir is considered as a special risk factor. The slope failure resulting in maximum volume of slide is considered for the analysis of impact. The impact of slide into the reservoir will affect it by reducing its storage capacity, generation of secondary waves travelling upstream. These waves may affect reservoir rim and dam structure adversely and need to be analyzed for various parameters like height and speed of wave, travel distance of wave, wave height at Dam impact, overtopping of wave and force of wave impact on Dam as in [8]. The wave action is shown in Figure 2.

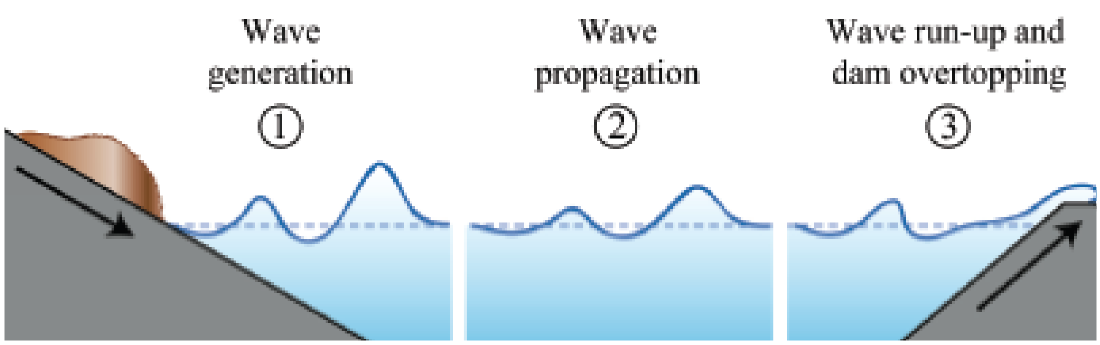

Figure 2 Wave generation due to slide impact

The individual risk rating are assigned after evaluating all the impact factors based on respective analyses and site specific parameters. The special factor is also obtained based on results of wave analysis carried out using computations developed in [9]. The total ratings of risk of impact of most critical slides of all zones are obtained as described in Table 9.

Table 9
Evaluation of total risk for the reservoir rim

Impact Risk factors		**Individual ratings**			
Factors	**Maximum Rating**	**Zone-1**	**Zone-2**	**Zone-3**	**Zone-4**
Slope stability	5	2.0	3.5	1.5	2.5
Local habitation	5	2.5	4.6	1.2	4.8
Local infrastructure	5	3.5	4.5	1.0	4.7
Special impact factor	5	1.5	4.5	1.7	2.5
Total rating	**20**	**9.5**	**17.1**	**5.4**	**14.5**
Risk	-	High	Low	High	Moderate

The risk categories of each zone are also determined from the total risk rating as shown in table 9. It is apparent that the zones are having a wide scatter in the total risk ratings, though the landslide hazard was relatively consistent. Risk zonation maps are generated for the reservoir rim area based on risk categories. Risk zonation map for zone 3 is shown in Figure 3.

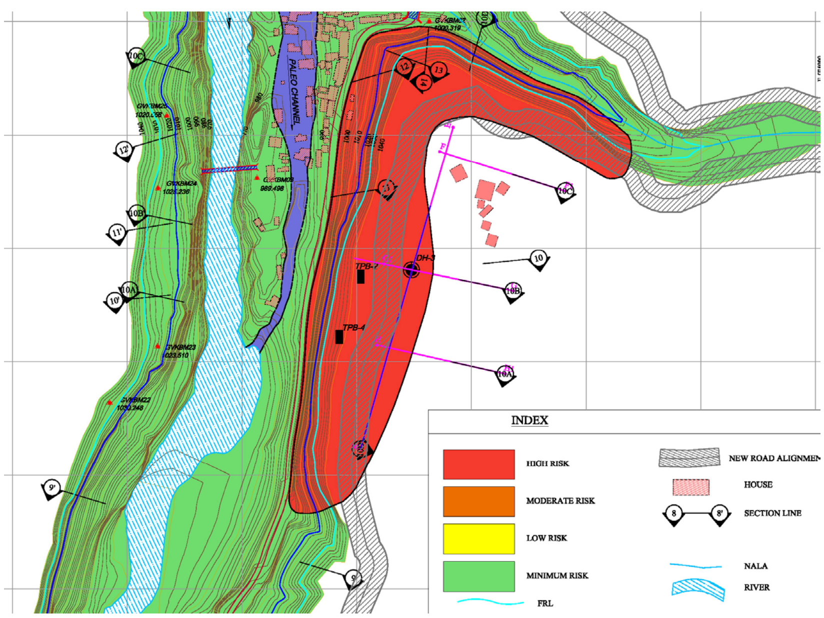

Figure 3 A Risk zonation map of zone 3 of reservoir rim

Landslide Control

The most effective measure to control the landslide is considered to be the strengthening of natural slopes. However, the methods adopted for slope strengthening are dependent on the site specific features like accessibility, gradient and stability of slope, material of slope, habitation and future development on the slope.

The objective of strengthening the slopes of a reservoir rim shall be to either eliminate the slides at all or to disintegrate a massive slide into multiple smaller slides.

The slope strengthening measures as suggested by GSI in [2] for soil overburden slopes were studied for all vulnerable zones in terms of suitability and most suitable methods are shortlisted for respective zone.

In general the landslide control can be optimized by considering the slope strengthening for the zones having total risk rating in the category of moderate, maximum and high risk of impact only. The suitable strengthening measures are analyzed according to the desired stability for all vulnerable slopes in zone 1, 3 and 4 respectively.

However, the implementation of the slope strengthening measures evaluated for respective zones can be prioritized based on the total risk ratings. Therefore, it is suggested that the zone 3 having the minimum risk rating shall be considered first for landslide control followed by zone 1 and 4 consecutively.

Similarly the landslide monitoring systems can be implemented after optimizing based on the total risk categorizes.

13. Conclusions:

A semi quantitative risk assessment approach based on impact of landslide has been presented in this paper to supplement the available guidelines and procedures for landslide hazard evaluation and zonation outlined by BIS and GSI. The total risk of landslide impact on the surrounding elements is estimated based on individual factors addressing the effect of slide on important features.

It is demonstrated in this paper that even if the landslide occurrence hazard can be similar on macro scale for various zones in an area, the risk associated with them can be altogether different.

The landslide hazard zonation on appropriate scale plays a vital role in identification of potential slide location and its severity. However, the total risk of landslide impact can be used to optimize the landslide mitigation measures and also to prioritize the implementation of such measures.

It is suggested that the impact of landslide on surroundings shall be given equal importance while evaluating the risk. There is an ample scope of developing scientific methods to account for each and every aspect of the risk of landslide impact.

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