



Precision modeling of slope stability for optimal landslide risk mitigation in Ramban road cut slopes, Jammu and Kashmir (J&K) India

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Abstract

The socioeconomic growth and development are extensively aided by the development of road networks in the Union Territory (UT): Jammu and Kashmir (J&K), a Himalayan state. However, due to complex geological factors, road cut slope instability is ubiquitous in the area, leading to frequent slope failures and interruption of transportation, loss of life, environmental deterioration and economic damage. To this direction, a comprehensive investigation was undertaken using field observations and variance in geological conditions at six different locations present along the routes linking Gool town of district Ramban with other neighboring villages in the area. The study carried out kinematic analysis and employs rock mass rating (RMR), geological strength index (GSI) and slope mass rating (SMR) techniques to characterize rockmass of the selected slopes for the stability assessment. A detailed structural analysis was carried out to understand the mechanism of slope failure in the area. The kinematic analysis reveals that joint planes cross at various angles, leading to diverse possible failure mechanisms with dominantly wedge failures, accompanied by a lesser occurrence of toppling and planar failures. Furthermore, the landslide possibility index (LPI) system was also used to assess the stability. The stability of the slopes has been identified to range from stable to entirely unstable. Based on the above data sets, a landslide susceptibility map was produced to demarcate the zones of high risk in the area. In addition to assisting with existing developmental projects in the region, the present study is well-positioned to aid in the mitigation of risks. The high-risk elements were also identified, and specific mitigation strategies are recommended for those elements.

Keywords Kashmir Himalaya · Slope stability · Slope mass rating · Rock mas rating · Kinematic analysis · Landslide possibility index

Introduction

The Himalayan region is a well-known for landslide incidences and slope instability problems as a result of structural and geological setup, regional climatic setup and dynamic regional geomorphological constitution (Fayaz et al. 2022). The slope instability is widely influenced by the presence of suitable and significant severe rainfall and snowfall events, and continuous neo-tectonic activity in the region (Singh et al. 2010; Ghosh et al. 2014; Nanda et al. 2021a; Choudhury et al. 2023; Zahoor et al. 2023a, b, c). Diverse rock types, intricate faults, folds, and fractures have been formed over the area's geological history as a result of tectonic pressures which has greatly affected rock slope stability in the region (Nanda et al. 2020). Nevertheless, during recent years, there has been a discernible increase in the number of anthropogenic activities in the region for developmental purposes, thereby contributing additional influencing factors

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for the unstable nature of the slopes in the fragile Himalayan terrain (Bhattacharya 2018; Nanda et al. 2021a, b; Shah et al. 2023). During recent years, a number of hydropower projects, human settlements, road networks constructions, etc. have been witnessed in the eco-geologically fragile Himalayan region (Chauhan et al. 2010; Pradhan and Oh 2011). The stability of this region is crucial for ensuring that vehicle traffic is safe and uninterrupted, reducing the loss of lives, limiting property damage, and protecting the environment in the surrounding area.

Similarly, in the Union Territory (UT): Jammu and Kashmir (J&K), a road networks of district Ramban has witnessed huge and astounding developmental and constructional activities during recent years (Ansari et al. 2022; Zahoor et al. 2023a). The road network serves as the sole means of communication between different villages of the district. The developmental activities have resulted in an increased frequency of major as well as minor landslide and slope instability episodes in the area (Menggenang and Samanta 2017; Aziz et al. 2023; Choudhury and Chaudhuri 2023). The slope instability problems are severe particularly during the monsoon and post monsoon seasons in the area (Mir et al. 2024). The inadvertent excavation and cutting of rock slopes for the purpose of road building and expansion has rendered the slopes highly sensitive and susceptible to different types of landslides incidences such as rockfalls, toppling, rock slides and debris slides etc. (Mousavi 2017; Hamid et al. 2023; Zahoor et al. 2023b). During the process of tunneling and road widening, the vibrations that are caused by blasting have the potential to cause the cracks in the rock to become more widespread and fragile (Nahayo et al. 2019; Xiao 2019; Ansari et al. 2023). The slope failure incidences generally cause traffic distraction on the connecting roads in the district causing inconvenience to inhabitants. At times, a huge and severe loss to property and life is also witnessed in the area (Mir and Gani 2019).

Therefore, to assess the stability condition along these roads is direly required so that the responsibility of maintaining and ensuring safety to the infrastructure and human life can be achieved. Furthermore, to comprehend the possibility of rock cut failures, many rock mass categorization methods have been developed. For instance, the Rock slope stability analysis uses state-of-the-art numerical techniques like the continuous, discontinuum, and hybrid approaches for the rock mass characterization. Similarly, the limit equilibrium method (LEM), finite difference method (FDM), finite element method (FEM), neural networks (NN), fuzzy logic (FL) and geographic information systems (GIS) are all examples of numerical and traditional approaches used for this purpose (Verma and Singh 2010; Sarkar et al. 2012; Ahmad et al. 2013; Singh et al. 2014). Empirical and numerical analyses are used to assess slope stability. (Anbazhagan et al. 2017). Additional, different empirical

methods developed and modified from time to time by researchers include Q-system (Barton et al. 1974), rock mass rating (Bieniawski 1976, 1989), modified slope mass rating (Anbalagan et al. 1992), slope mass rating (Romana 1985, 1995), Chinese slope mass rating (Chen 1995), continuous slope mass rating (Tomás et al. 2007), modified slope mass rating (M-SMR) (Rahim et al. 2009), slope stability rating (SSR) (Taheri and Tani 2010), fuzzy slope mass rating (FSMR) (Daftaribesheli et al. 2011), new slope mass rating (NSMR) (Singh et al. 2013), slope quality index (SQI) (Pineiro et al. 2015), continuous rock mass rating (Rad et al. 2015). Since its inception the rock mass rating (RMR) has proven to be an invaluable instrument for characterizing rock masses for use in engineering planning and design (Bieniawski 1974).

The main benefits of RMRs is its simplicity, ability to assess rock quality across the surface and subterranean activities at every site level, and its role in describing empirical connections like the Hoek–Brown failure criteria (Marinos et al. 2006). The rock strength revealed on slope face, spacing of discontinuities, condition of discontinuities, the orientation of discontinuities, and groundwater condition are all essential to the RMR approach. However, there are certain restrictions for RMR involving various engineering geology issues. But, to overcome these restrictions, RMR shall be used together in conjunction with geological strength index (GSI). The GSI is frequently utilized for the rapid and qualitative evaluation of rock masses as well. For the estimation of GSI, Hoek and Brown (1997) suggested a graph to calculate it by taking into account both rock properties and the condition of discontinuities. Furthermore, several SMR methods were also used to evaluate the stability of selected slopes which included SMR (Romana 1985) and Chinese SMR (Chen 1995). Romana (1985) developed SMR by enhancing the original RMR with four correction factors which are substantially more decision-based and discrete. Topple and planar failure ratings were the first to be included into SMR; Anbalagan et al. (1992) then added ratings for wedge failure. Chen (1995) devised the Chinese slope mass rating (CSMR) by including two coefficients into the standard SMR formula. Both the slope height and the kind of slope discontinuity are taken into consideration by these two factors. The slope height coefficient is only valid for slopes that are higher than 80 m, but the discontinuity coefficient takes into consideration lengthy weak seams, unbroken bedding planes and continuous bedding planes.

In the present study, rock mass categorization has been carried out for the purpose of determining the degree of instability along the road connecting different villages of Gool town with the district headquarter located at Ramban district, UT, J&K-a Himalayan state. A comprehensive methodology that integrates numerical and empirical techniques is used in the proposed study. In spite of the fact that

previous research has addressed slope stability difficulties in a number of different places, the unique challenges that are provided by slope instability in this region are still relatively underexplored. Contemplating this, Kinematic analysis, in conjunction with methods like rock mass rating (RMR) and geological strength index (GSI) and various other slope mass ratings in addition to landslide possibility index (LPI) were used to determine the stability state of each slope. In order to ascertain the most likely mechanism of failure in the study area, kinematic analysis was carried out to demonstrate a link between the surface topography and the discontinuity direction.

Study area

The study area lies in the District Ramban of Jammu and Kashmir, India. The road runs parallel to NH-1A and connects the different villages and hamlets to the district headquarters of Ramban. It is traversing through the rugged terrains of the Pir Panjal mountain range in the Lesser

Himalayas. The coordinates of the area are 33° 14' 12.16" to 33° 15' 58.61" N and 75° 14' 18.80" to 75° 00' 17.60" E (Fig. 1). The road network forms the sole means of connection in the region. Over the last several decades, there has been a surge in growth of human population and developmental activities in the region. The development necessitated the extension of existing roadways leading to slope cutting and road widening (Aziz et al. 2023; Es-smairi et al. 2023; Mir et al. 2023). The road widening and slope cutting threatens the stability of the slope due to the use of weak and unreliable procedures. This route also accommodates the transportation of raw materials, machineries, and other equipments for the Sawlakote hydel power plant, which is now under development, and other mineral quarries that are being approached in conjunction with other tourist destinations. The abundant visibility of slope material and the diverse array of slope aspects generated along the road and neighboring region need a thorough examination of stability slopes in the area. In the study area, maximum summer time temperatures of 42° is recorded near the foothills of the research region, but as towards higher elevation, the

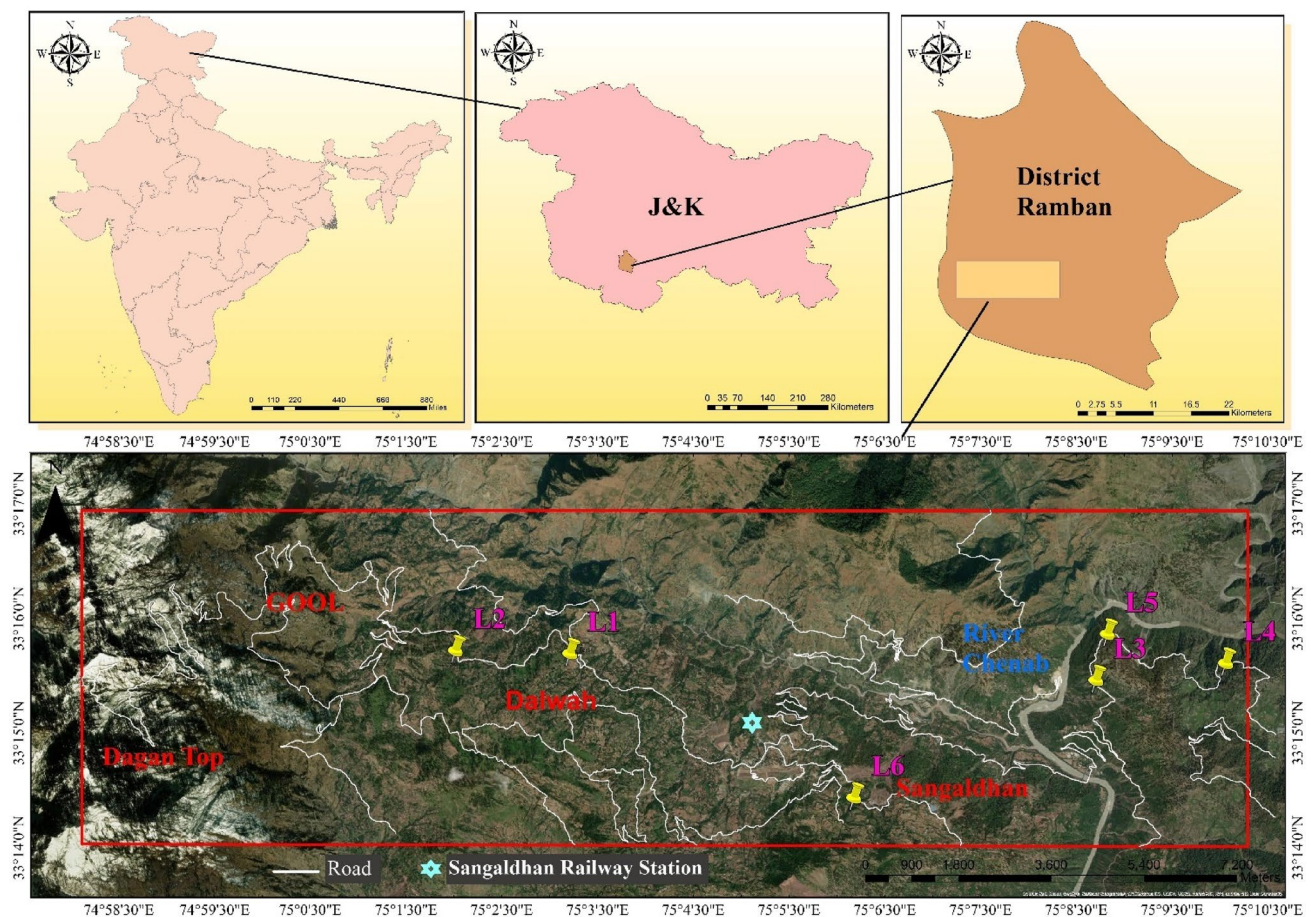


Fig. 1 HYPERLINK "sps:id::fig1|locator::gr1|MediaObject::0" Study area map showing selected sites under investigation with topographic variations

temperature drops to sub-zero. Precipitation occurs mostly as rain in the summer, particularly between July and September, and as snow in the winter, especially at higher elevations.

Geology of the study area

The study area forms a part of Lesser Himalayas and geologically the area has emerged from the Himalayan orogenic movements. The area displays the geological rock formation sequence ranging in age from Precambrian to Miocene periods. Various geological formations present in the area include Upper and lower Murree formations, Ramban formation, Gamir and Baila formation. Major part of area falls in the Murree group of rocks along with Ramban formation (Fig. 2). Murree rock formation is predominately composed of alternate beds of sandstones, siltstones, claystones and shale with ripple marks and pseudo-conglomeratic structure. The Ramban formation comprises shale, slate, limestone and quartz-arenite and overlies Baila formation. Thin greenish colored slate beds of Ramban formation are well exposed along some parts of the road network. A major north dipping discontinuity known as Murree Thrust crosses the area near Dharam Village. The Murree Thrust separates the younger Murree rocks from the overlying older Dogra slates of Precambrian age. This discontinuity for being youngest and active provides most favorable site for slope failures in the area. Another Thrust viz; Saladar Thrust has merged with Murree Thrust in the vicinity of Sangaldan area. Due to the

presence of Saladar Thrust and Murree Thrust, rocks in this area are highly deformed, faulted, crushed and jointed. The rock exhibits high levels of fracturing, as evidenced by the presence of joint sets consisting of two or three joints.

Materials and methods

In this study, six locations were evaluated for stability analysis (Table 1). The study used a modified GSI table (which includes five categories of structure rating and surface condition rating) to categorize rock masses in the area. For this purpose, field work was carried out from 25th January to 3rd February 2022. For the estimation of the structural data sets, the Brunton compass was used. For the estimation of engineering properties of rocks, the Schmidt hammer was used. It provides a quick and inexpensive measure of surface hardness that is widely used for estimating the mechanical properties of rock material. Furthermore, a 1:50,000 geological map of the study area was

Table 1 Location of studied sites

Location	Latitude	Longitude
L1	33° 15' 42.31" N	75° 3' 13.68" E
L2	33° 15' 43.90" N	75° 2' 1.99" E
L3	33° 15' 28.30" N	75° 8' 43.34" E
L4	33° 15' 37.25" N	75° 10' 4.74" E
L5	33° 15' 52.56" N	75° 8' 50.65" E
L6	33° 14' 26.87" N	75° 6' 11.70" E

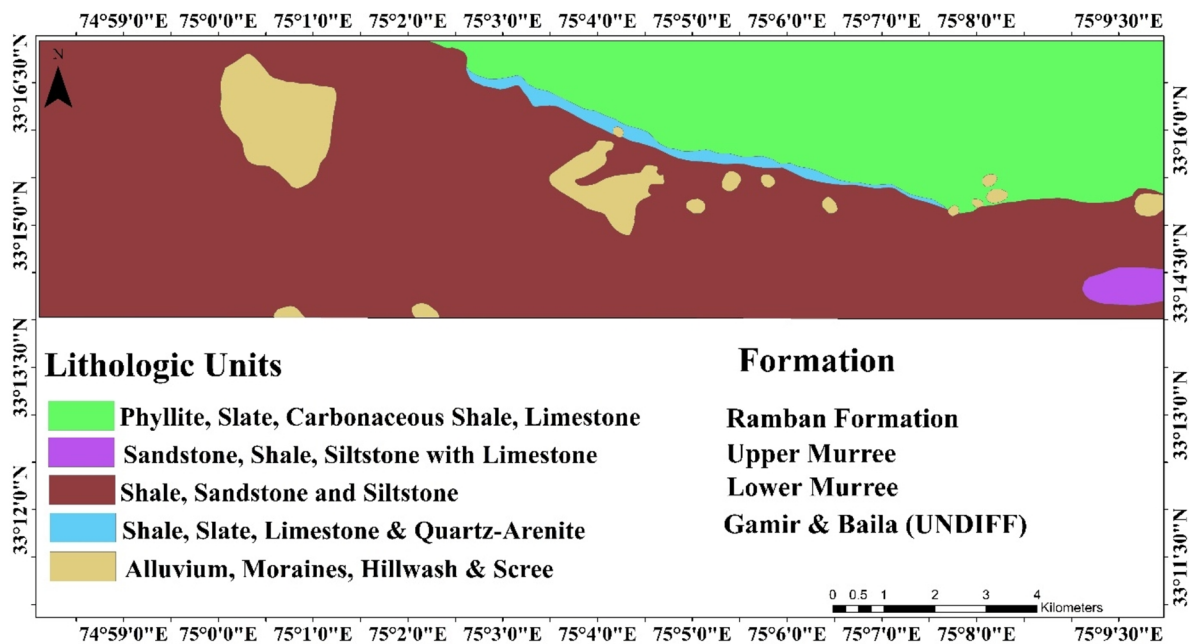


Fig. 2 Lithology of the study area illustrating geological formation

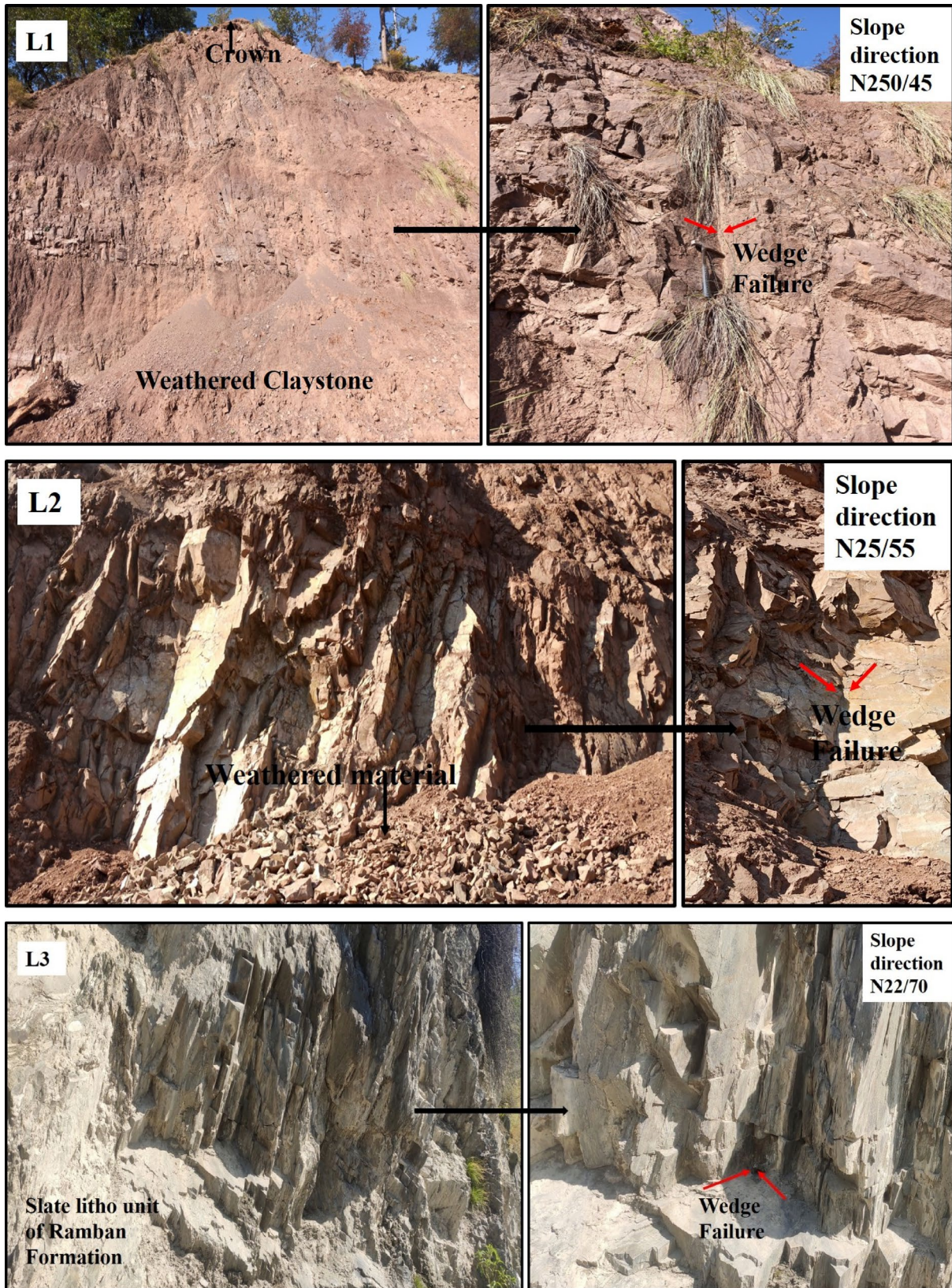


Fig. 3 Selected site locations showing regional geological variations

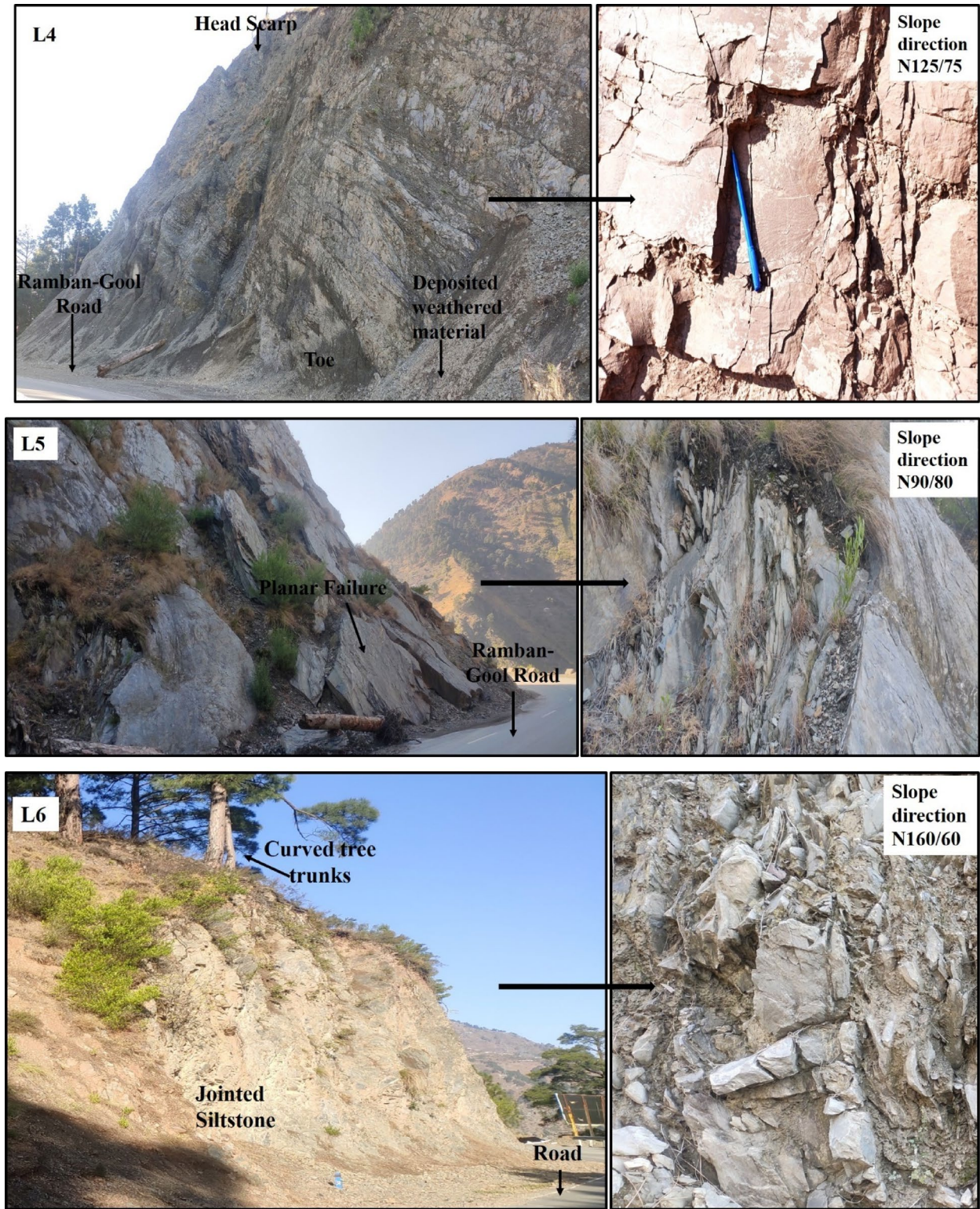
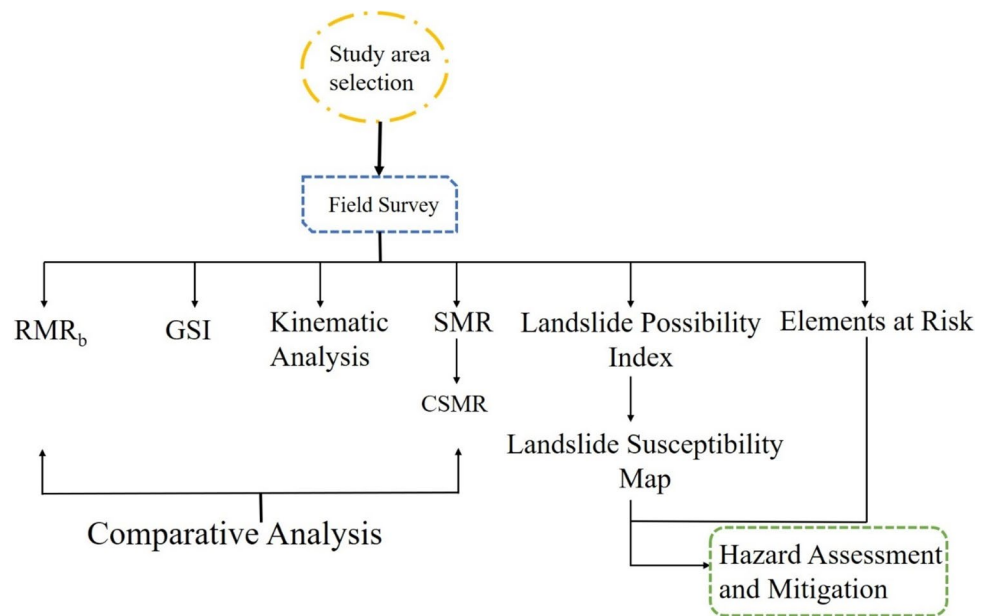


Fig. 3 (continued)

Fig. 4 Flowchart illustrating the comprehensive technique employed for the investigation



used for field study (GSI 2012). During the field work detailed information on the volume of the joints and their nature was collected at six locations along the routes linking Gool town and other villages in the vicinity with the district headquarters Ramban (Fig. 3). The slope height for all these selected sites was estimated. A slope height of less than 75 m with varying slope angle ($> 45^\circ$) was found at different locations. Due to its active tectonic history, the region is very deformed; two and even three sets of joints are regularly developed. The attitude data and estimated, and other unique features of joint sets were meticulously collected in the field. For each joint set, spacing and condition of the discontinuities, along with the slope’s physical conditions were collected in detail.

In the present study, the RMR, GSI and SMR techniques were used to characterize rock mass of the selected slopes. The RMR_b and GSI were determined on the basis of the field data acquired from the area. One of the most crucial factors in determining RMR_b and GSI is the rock quality designation (RQD). The RQD was estimated by using the volumetric joint method. Empirical equation based RMR_b , field data, and kinematic analysis were used to get the SMR values in the area. Moreover, a comparative analysis of the stability methods was also carried in the study (Fig. 4). The landslide possibility index (Bejerman 1994) approach was also chosen in addition of above methods, for evaluating stability due to its simplicity, practicality, and capacity to extrapolate actual field conditions. Utilizing the derived LPI values, the area is divided into different zones of landslide susceptibility. The elements at risk were also mapped and derived using Sentinel 2 image with 10 m resolution using ArcGIS 10.3 version. In addition to this, five elements susceptible to potential damage from landslides were identified in the current area and include human settlements,

road, forest area, grassland, and barren land cover. The brief description of the parameters evaluated is given below:

Rock mass rating (RMR_b)

The five parameters which include strength of intact rock, spacing of discontinuities, RQD, condition of discontinuities and groundwater conditions were evaluated for determining the basic RMR values for all selected six sites. The Schmidt rebound hammer was used to measure the uniaxial compressive strength (UCS) of the material in its natural environment. The UCS value for all the locations varied from 22 to 35 MPa. A mean value estimated for each location was considered as final UCS. The volumetric joint count was used to estimate RQD. An empirical equation based on joint volume was used to estimate RQD (ISRM 1978), as follows:

$$RQD = 115 - 3.3Jv \tag{1}$$

Joint volume (Jv) was calculated during field investigation by considering the number of joints per 1 m^3 of space area, within which jointing occurs mostly as joint sets. During the field survey, ratings of surface conditions, joint spacing, and ground-water condition were analyzed. Utilizing all the collected data and using Eq. (2), the RMR_b was calculated as

$$RMR_b = R_{UCS} + R_{RQD} + R_{JS} + R_{JC} + R_{GWC} \tag{2}$$

UCS is uniaxial compressive strength (in MPa); JS is joint spacing (in meters); RQD is rock quality designation (%); JC is joint condition (in meters), Jv is volumetric joint (number of joints/ m^3); and GWC is ground-water

Landslide Possibility Index (LPI)							
No.	Factor	Scale	Estimation	No.	Factor	Scale	Estimation
1	SLOPE HEIGHT (M)	1 – 8 m	1	2	SLOPE ANGLE (°)	< 15°	0
		9 - 15 m	2			15° - 30°	1
		16 – 25 m	3			30° - 45°	2
		26 – 35 m	4			45° - 60°	3
		> 35 m	5			> 60°	4
3	GRADE OF FRACTURE (Number of Fracture)	Sound	0	4	GRADE OF WEATHERING (Alteration and compressive strength)	Fresh	0
		Moderately Fractured	1			Slightly Weathered	1
		Highly Fractured	2			Moderately Weathered	2
		Completely Fractured	3			Highly Weathered	3
						Completely Weathered	4
				Res. Soil	5		
5	GRADIENT OF THE DISCONTINUITIES (°)	<° 15	0	6	SPACING OF THE DISCONTINUITIES (M)	3 <	0
		15° - 30°	1			3 - 1	1
		30° - 45°	2			1 - 0.3	2
		45° - 60°	3			0.3 - 0.05	3
		> 60°	4			0.05 >	4
7	ORIENTATION OF THE DISCONTINUITIES	Favourable	0	8	VEGETATION COVER (%)	Void (<20%)	0
		Unfavourable	4			Scarce (20% -60%)	1
9	WATER INFILTRATION (mm/year)	Inexistent	0	10	PREVIOUS LANDSLIDES (m³/year)	Not registered	0
		Scarce	1			Registered Small volume (<3m³/year)	1
		Abundant (>500mm/year) Permanent	2			Registered High volume (>3m³/year)	2
		Abundant (>500mm/year) Seasonal	3				
<div style="border: 1px solid black; padding: 5px; display: flex; justify-content: space-around; align-items: center;"> 1 + 2 + 3 + 4 ± 5 + 6 + 7 + 8 + 9 + 10 = LPI value </div>							
The LPI value is obtained by adding the estimations of attributes 1 to 10. If the orientation of the discontinuities is favourable, subtract the estimation of the gradient.							
I (Nil) (0-5)		III (Moderately low) (11-15)		V (High) (21-25)			
II (Low) (6-10)		IV (Moderately high) (16-20)		VI (Very high) (>25)			

Fig. 5 LPI chart followed for the present study (After Bejerman 1994)

Table 2 Class of landslide failure possibility for different LPI values (After Bejerman 1994)

LPI range	Category	Failure possibility
0–5	I	Small
6–10	II	Very Low
11–15	III	Low
16–20	IV	Moderate
21–25	V	High
>25	VI	Very High

condition. RMR_b is the basic RMR value and R_{UCS} , R_{RQD} , R_{JS} , R_{JC} , and R_{GWC} are the rankings of UCS, RQD, JS, JC, and GWC from the Bieniawski (1989) table.

Table 3 Landslide hazard classification as per LPI range (After Bejerman 1994)

Hazard category	LPI range
Low	1–10
Moderate	11–20
High	>21

Geological strength index

For the closely jointed and heterogeneous rock mass characterization, the used of GSI is most popular method. It fixes the issue such as, inconsistency of RQD value in case of weak rocks, faced by using the RMR_b technique for rock mass characterization. In this study, the quantitative GSI was determined based on two ratings such as Structure

rating (SR) and Surface condition rating (SCR). The data collected in the field was used to rate SR and SCR. The value of SR was determined by J_v using Eq. 3 whereas, Eq. 4, was used to determine the SCR by summing the ratings for weathering, roughness, and infilling. The quantified GSI values were plotted on the chart (Sonmez and Ulusay 2002).

$$SR = -17.5 \ln(J_v) + 79.8 \tag{3}$$

$$SCR = R_R + R_W + R_I \tag{4}$$

where, the SR represents structure rating and SCR represents surface condition rating. Roughness, weathering and infilling is represented by R_R , R_W and R_I respectively.

Slope mass rating (SMR)

Romana (1985) developed the slope mass rating (SMR), a global rock mass classification that extends the RMR_b by adding correction variables for use in rock slope engineering. SMR was computed using the following formulae

$$SMR = RMR_b + (F_1 \times F_2 \times F_3) + F_4 \tag{5}$$

Here F_1 , F_2 and F_3 are correction factors for discontinuity orientation while as F_4 represents method of excavation. In this work, the F_4 value is considered as -8 in order to take into account the worst-case situation.

Chinese slope mass rating (CSMR)

The distinct slope mass rating method, Chen (1995) was also used which introduces two more variables to the original SMR equation. The slope height factor, denoted by " ξ " and the discontinuity factor, denoted by " λ " are the two additional variables considered for CSMR which is calculated by Eq. (6).

$$SMR = \xi RMR_b + \lambda (F_1 \times F_2 \times F_3) + F_4 \tag{6}$$

where,

$$\xi = 0.57 + 0.43 \times 80/H \tag{7}$$

The value of ξ is calculated from Eq. (7) for slopes with H greater than 80 m while as ξ is taken equal to 1 for slopes with H less than 1. In the present study the slope height as estimated from filed field investigation was less than 80 so, the value of ξ is considered as 1. The value of λ is considered 1 for log seem faults filled with clay, λ is 0.8 or 0.9 for gouge filled large scale joints and λ is 0.7 for joints in tightly interlocked bedding planes. In current study we considered the value of λ as 0.7 as the joints were tightly interlocked.

Kinematic analysis

A kinematic analysis was carried out to show how the presence of negatively oriented discontinuities might lead to several types of rock slope failures (wedge, plane). Markland's test, as described by Hoek and Bray (1997), was used for this study. Kinematic analysis was performed using Rock Science's Dips 7.0 program. The program allows for the user to enter the slope angle and friction angle. In response, a template is superimposed over the stereonet to bring emphasis to the vulnerable area. A critical zone legend is generated automatically based on the number of plane crossings or poles in the critical zone.

Landslide possibility index

The assessment of slope stability was also conducted by employing the landslide probability index (LPI). The LPI system entails the examination of ten primary characteristic features that encompass structural, geological, geomorphological and hydrological variables within a certain area (Fig. 5). Each attribute possesses a spectrum of values, and the estimation and quantification of each feature is conducted in the field according to the defined technique outlined by Bejerman (1994). The LPI for a slope is calculated by adding the anticipated values of 10 parameters, as indicated in the following Eq. (8).

Table 4 Ratings given to different parameters for determining RMR_b

Slide	UCS	RQD	GWC	Js	Joint surface condition (Js)					RMR
					Persistence	Aperture	Roughness	Weathering	Infilling	
L1	4	17	7	15	4	4	3	3	2	59
L2	4	17	15	15	2	5	3	3	2	66
L3	4	13	15	8	4	5	1	5	2	57
L4	4	17	15	10	1	5	5	3	6	66
L5	4	17	10	10	4	5	1	3	2	56
L6	4	17	15	10	4	6	1	1	6	64

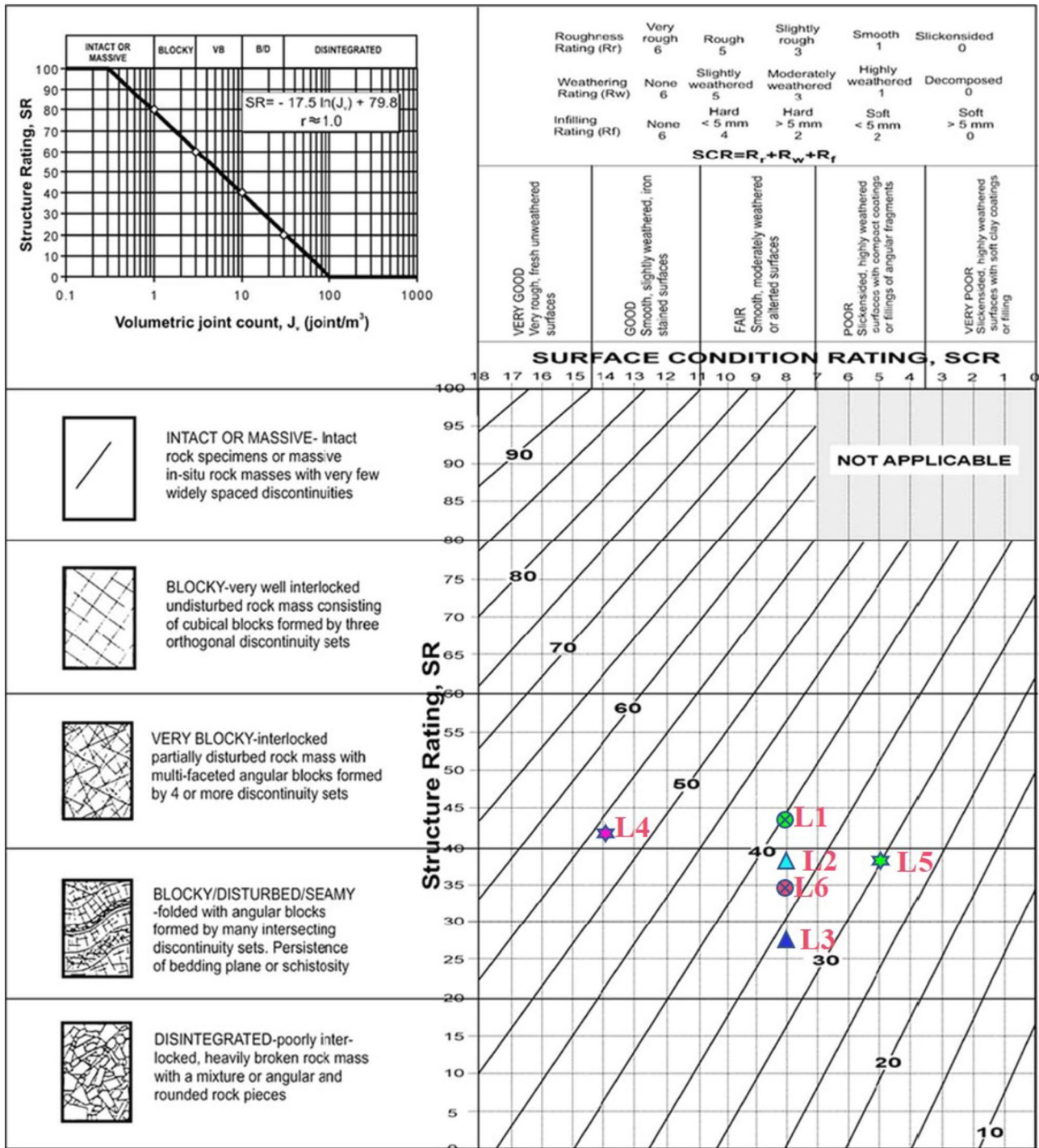


Fig. 6 GSI values plotted on GSI chart (Sonmez and Ulusay 2002)

$$LPI = \sum_{i=1}^{10} = 1 + 2 + 3 + 4 \pm 5 + 6 + 7 + 8 + 9 + 10 \quad (8)$$

In cases where the discontinuities are oriented in favorable manner, the calculated magnitude of the discontinuity gradient is deducted from the overall LPI to rectify the LPI

calculation. The assessment of the slope's hazard level is established by evaluating the LPI value, which is derived from the summation of 10 estimated parameters. A heuristic technique was utilized in order to integrate the parameters. Consequently, the potential failures of slopes are categorized into six distinct classifications, as outlined in Table 2.

Table 5 Type of failures revealed by kinematic analysis

Location	Slope direction	Joint set (Dip/Dip direction)				Type of failure
		J0	J1	J2	J3	
L1	N250/45	45/15	60/285	52/190	–	W
L2	N25/55	50/255	70/10	58/20	78/N285	W, T
L3	N22/70	40/25	80/275	75/205	60/N150	W, T
L4	N125/75	25/300	76/78	75/98	83/N175	W
L5	N90/80	28/280	83/60	80/120	–	W, P
L6	N160/60	20/30	80/110	63/205	–	W

Furthermore, by utilizing the designated LPI category for each rock slope, it becomes possible to assess the landslide hazard associated with that slope. Bejerman classified hazards into three groups, as presented in Table 3.

Results and discussion

Rock mass characterization and slope stability

In the studied region Extensive structural mapping and geological investigation was carried out along the road network from 25th January to 3rd February 2022. Six slopes were assessed for their vulnerability by measuring LPI and RMR_b , SMR, GSI for rock mass characterization. Rockmass are mostly sandstone, silt and phyllite is also observed at some places. The RMR_b calculated for slopes L2, L4 and L6 show good classification of rockmass representing category II while as rest of slopes show fair classification representing category III (Table 4). Only two slopes (L1 and L2) had wide joint spacing while as rest of the slopes had closely spaced joints. Weathering for all the slopes varied from low to moderate with rough to smooth roughness. The persistence of joints as studied in the field varied from 1 to 5 m. The infilling material for all the slopes was clay. Two slopes (L1 and L5) had water flowing conditions whereas the rest of slopes were observed to be with dry conditions.

Results of quantified GSI reveal that L1 and L4 have very blocky structure with good and fair surface conditions for L4 and L1 respectively. However, sites L2, L3, L5 and L6 have blocky/disturbed structure with L5 having poor surface condition and the rest having fair surface conditions. The different values of quantified GSI falling in the range of 32–55 (Fig. 6).

The joints in rocks are in sets of two or three, making it clear that the rock is highly fractured. The kinematic analysis for the selected sites has also been analyzed so as to identify the failure mechanisms. Kinematic study revealed all three possible failure mechanisms (planar, wedge, and topple) in the area. The kinematic analysis findings confirm the failure mechanisms detected in the field investigation. The joint patterns shown by the kinematic analysis point

to a predominance of wedge failures, with some toppling and planar failures (Table 5). In stereographic projection, the pink area represents the critical zone of failure for all six sites.

The SMR findings demonstrate that the sites examined fall in the stability class of different ranges varying from III (stable) to V (completely unstable), as illustrated in Fig. 7. Different failure mechanisms have been assigned different scores for the various slopes. The SMR analysis also revealed a spectrum of slope stabilities, depending on the failure mechanism, for example for the site L5, the wedge failure falls in the category IV (unstable) whereas the two planar failures fall in III category (partially stable) (Table 6).

According to the results, the Chen (1995) values turned out to be greater than the SMR values (Table 7). Nonetheless, the slopes indicate identical stability classes in both the SMR and CSMR methods, with the exception of slope L5 (wedge) and L6. The stability class for slope L6 by SMR technique is unstable while as by CSMR technique it comes out to be partially unstable category. SMR and CSMR both show the two planar failures (north-west and south-west direction) in L5 are partially stable but in the case of wedge failure, SMR is completely unstable where as CSMR is unstable. The results from both the techniques (SMR and CSMR) are compared in Fig. 8.

Table 8 presents the results of the LPI assessment performed on the slopes that were evaluated. The calculated LPI values at slope sites L1, L4, L5 and L6 are 23, 23, 25 and 22 respectively. These values suggest a high likelihood of failure at these slopes, also indicating “High” potential of failure and a “High” degree of hazard. The slopes exhibit a notable steepness, extensively fragmented and weathered rock formations, and unfavorable alignment of structural discontinuities. On the other hand, slope sites L2 and L3 both have LPI value 18 indicating the “Moderate” possibility of failure and hazard at these locations. The level of risk and likelihood of failure for each of the examined slope sites is depicted in Fig. 9.

A map illustrating the distribution of elements at risk reveals that 40% of the region is held by forest, 48% by grassland, 1.1% by human settlements, 9.4% by barren

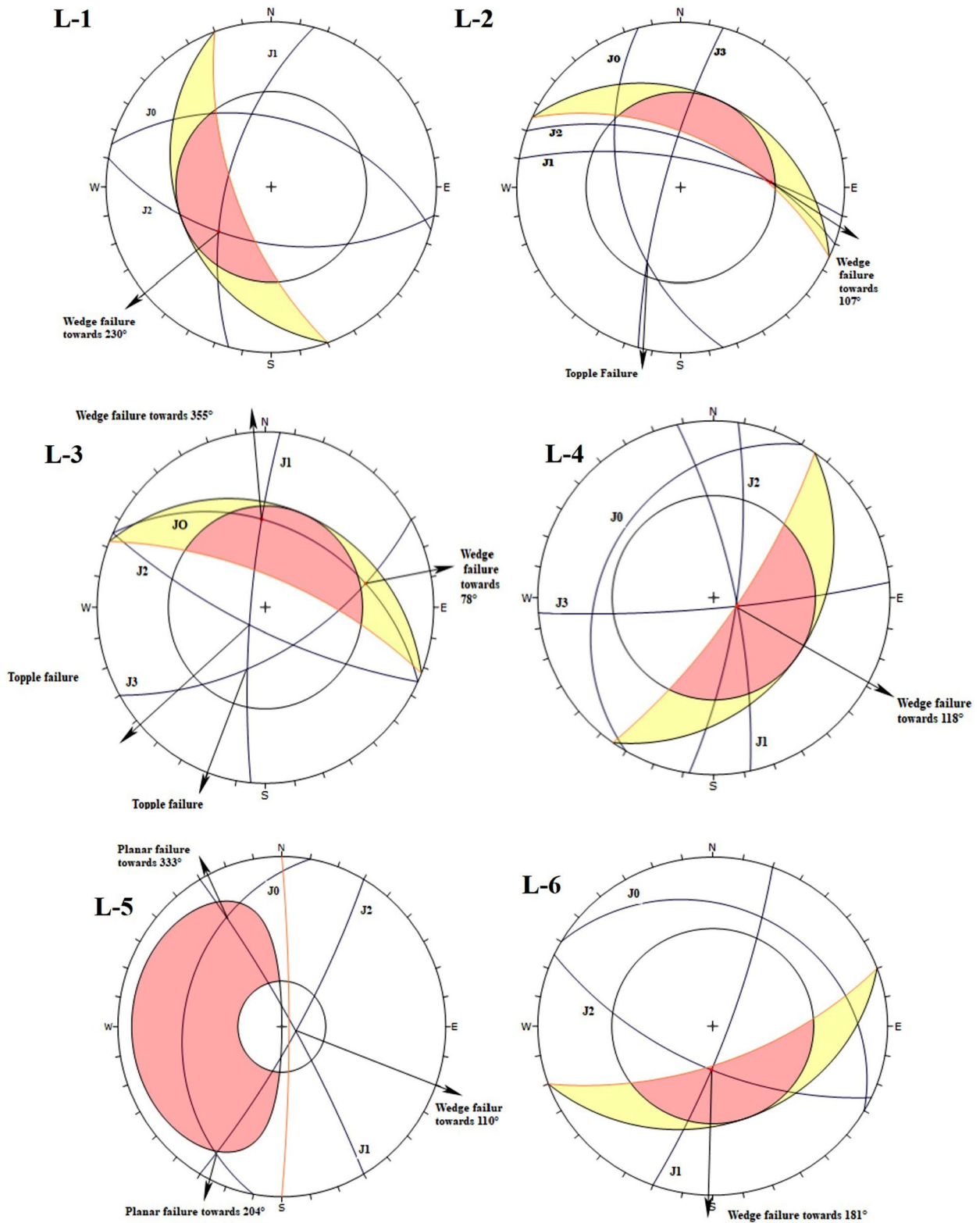


Fig. 7 Stereographic projection of studied sites

Table 6 Stability analysis by Romana (1985) technique

Location	Failure type	Slope mass rating		
		Rating	Category	Stability class
L1	W	30.6	IV	Unstable
L2	W	56.65	III	Partially stable
	T	58	III	Partially stable
L3	W	45.4	III	Partially stable
	W	42.7	III	Partially stable
	T	43	III	Partially stable
	T	39	IV	Unstable
L4	W	15.5	V	Completely unstable
L5	W	28	IV	Unstable
	P	46.65	III	Partially stable
	P	46.65	III	Partially stable
L6	W	36	IV	Unstable

Table 7 Stability analysis by Chen (1995) technique

Location	Failure type	Chinese slope mass rating		
		Rating	Category	Stability class
L1	W	36.7	IV	Unstable
L2	W	57.1	III	Partially stable
	T	58	III	Partially stable
L3	W	46.48	III	Partially stable
	W	44.59	III	Partially stable
	T	44.8	III	Partially stable
	T	42	III	Partially stable
	W	28.25	IV	Unstable
L5	W	31.17	IV	Unstable
	P	47.06	III	Partially stable
	P	47.06	III	Partially stable
L6	W	42	IV	Partially stable

land, and 0.2% by roads within the study area (Fig. 10). Using the LPI values of selected sites, a landslide susceptibility developed for the study area, illustrating the overall vulnerability to landslides (Fig. 11).

Landslide hazard assessment

The most common types of damages brought on by landslides include property and land loss, as well as human injuries and fatalities. Landslide damage might be localized to the site of the landslide or it can spread out and threaten numerous aspects of the local environment. But, establishing a metric to assess the probability and simultaneously delineating areas depending upon the likelihood of getting impacted by landslides is crucial. The rock mass classifications are highly important for characterizing rock masses,

particularly for assessing the vulnerability of slopes. The analysis of the rock mass properties of the studied slopes in the region employing various approaches indicates that the slopes range from somewhat stable to unstable, and in some cases, completely unstable. In addition to this, the LPI values derived for the slopes also show failure possibility of Moderate to High. This revealed that the central portion of the study area contains geological sites characterized by rocks and soils that exhibit a lack of cohesion and stability. These materials include clay, silt, and unconsolidated substances, all of which contribute to a heightened susceptibility to slope failures in the nearby vicinity. Moreover, the vulnerability of this area is further compounded by its exposure to frequent and substantial precipitation, prolonged periods of rainfall, snowmelt events, and erratic weather patterns. These environmental factors can saturate the soil, increasing its overall weight while concurrently diminishing its shear strength. This dual effect significantly raises the likelihood of soil and rock masses becoming prone to sliding or experiencing landslides. Furthermore, the region is notably susceptible to seismic activity, experiencing a significant number of earthquakes. These seismic events have the potential to shake the ground and disrupt the equilibrium of slopes, thereby amplifying the likelihood of landslides in this geological context.

Mitigation measures

Based on the results of stability assessment and the prevalent failure causes, certain measures are recommended for landslide mitigation in the area. For instance, a series of corrective procedures and including shortcreting to fix weathered and loose material on slope. To prevent the collapse of poor rock units with distant joints, rock anchors can be installed. Benches should be built with sufficient widths so that they do not serve as straight rock falls. The volume of surface runoff water and groundwater seepage can be lowered by constructing back slope and mid-slope drains. Similarly, proper zoning and land-use regulations can help prevent construction in vulnerable areas or require specific engineering measures for developments in landslide-prone regions. The landslides zonation map presented in this study can be used as an essential tool for managing stability of the ongoing tunneling projects in the Himalayas. It will support engineers in making knowledgeable choices at each step of a tunnel project, from planning and design through building and long-term maintenance. They assist in identifying, assessing, and mitigating landslide hazards. Tunneling experts may improve the security and dependability of tunnel infrastructure in landslide-prone locations by adding these maps into their risk management tactics. Continuous monitoring of slopes using geotechnical instruments and the establishment of early warning systems can provide advance notice of

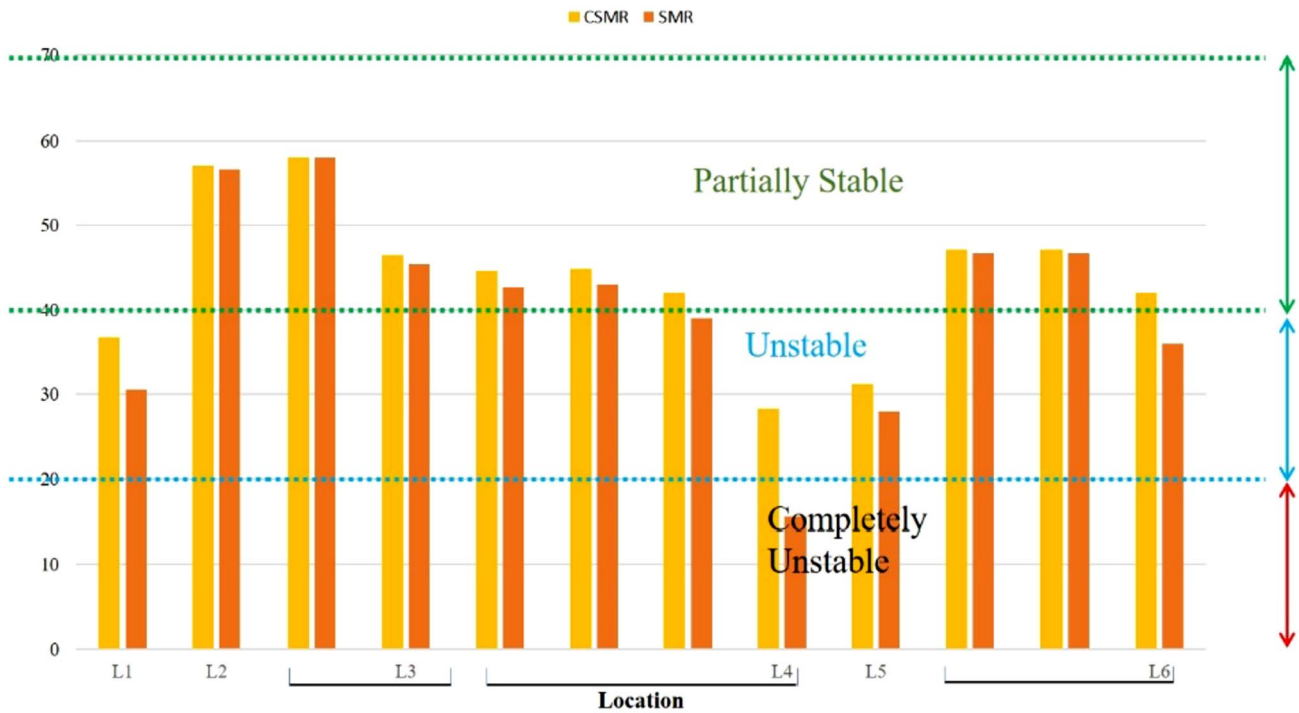


Fig. 8 Comparative analysis of SMR and CSMR technique

Table 8 Calculated LPI values for the slopes under study

No.	Parameters	Investigated slopes					
		L1	L2	L3	L4	L5	L6
1	Slope height	2	1	1	2	3	2
2	Slope angle	2	3	4	4	4	3
3	Grade of fracture	2	2	1	1	1	2
4	Grade of weathering	2	2	1	2	2	3
5	Gradient of discontinuity	3	3	3	4	4	3
6	Spacing of discontinuity	3	2	4	4	4	4
7	Orientation of discontinuity	4	4	4	4	4	4
8	Vegetation cover	1	0	0	0	0	1
9	Water infiltration	3	0	0	0	1	0
10	Landslide history	1	1	0	2	2	0
Landslide possibility index		23	18	18	23	25	22
LPI category		V	IV	IV	V	V	V
Failure possibility		H	M	M	H	H	H
Hazard category		H	M	M	H	H	H

H high, M moderate

impending landslides. These systems are designed to detect and alert relevant authorities and communities to impending landslide events well before they occur. This advanced notice allows for proactive response measures, potentially saving lives and minimizing property damage.

Conclusion

The slope failure in areas with high susceptibility to landslide hazards is a complex issue influenced by geological, topographical, climatic, and human factors. The Gool town and other villages in the vicinity with district headquarters

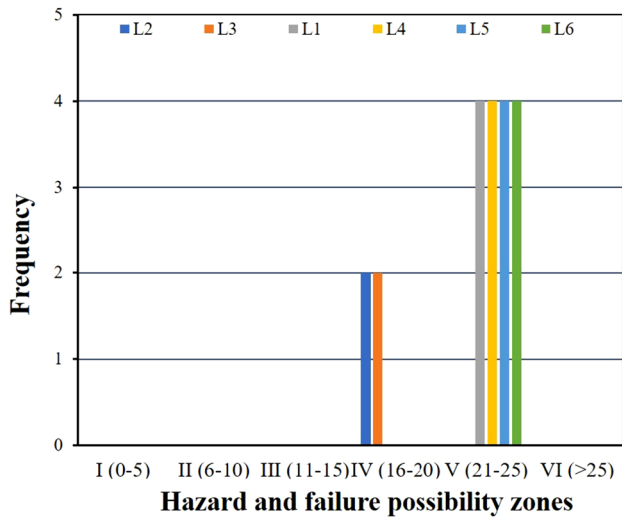


Fig. 9 Hazard and failure zones of studied slides

Ramban UT: J&K- a Himalayan state is both structurally regulated and dynamically active which necessitates to classify rock masses and to demarcate the region into different landslide hazard zones for prevention of human and property losses. In order to estimate the susceptibility of slopes, rock masses were characterized by kinematic analysis and rock mass classifications were undertaken at several sites. In this study, empirical approaches, were used for the evaluation of slope stability analysis. The analysis indicated that the RQD range from 55 to 88%, indicating low to medium level of resistance to weathering as per the slake durability index

test. The RMR_b indicated that the slopes L2, L4 and L6 belong to “Good Rock” while as slope L1, L3 and L5 belong to “Fair Rock” in rock mass classification. Also, the results from GSI revealed similarity with the RMR_b with an exception to L5 which fall in “Poor Rock” category. The stability of selected slopes was also assessed through the utilization of SMR and CSMR and the results show although higher values of CSMR than SMR but the stability class remained same. These empirical results show that the region requires appropriate long-term stability treatment procedures and well-managed programs to reduce the incidence of landslides and minimize material and human damage.

The kinematic analysis indicated that the Wedge failure was prevalent in the area with some toppling and planar failures at certain locations. Thus, stabilizing the road cut slopes using empirical methods is the fastest and most effective alternative in the treacherous terrains. The LPI assessment conducted on the examined slopes indicated that four out of six slide places are classified as having a "High" likelihood of experiencing landslides, hence presenting a "High" level of landslide hazard. In the case of potentially unstable zones in the Himalayas, such an agile rock mass stability evaluation is necessary for maintaining and constructing new roadways. Based on the results of the stability analysis and the most common failure modes, we recommend mitigation measures such as shortcreting for treating the weathered material that is found on the slope faces. To prevent the collapse of unfavorable rock units with widely separated joints, rock anchors can be installed. Effective risk management and mitigation strategies are essential to reduce the potential impact of landslides on lives and property.

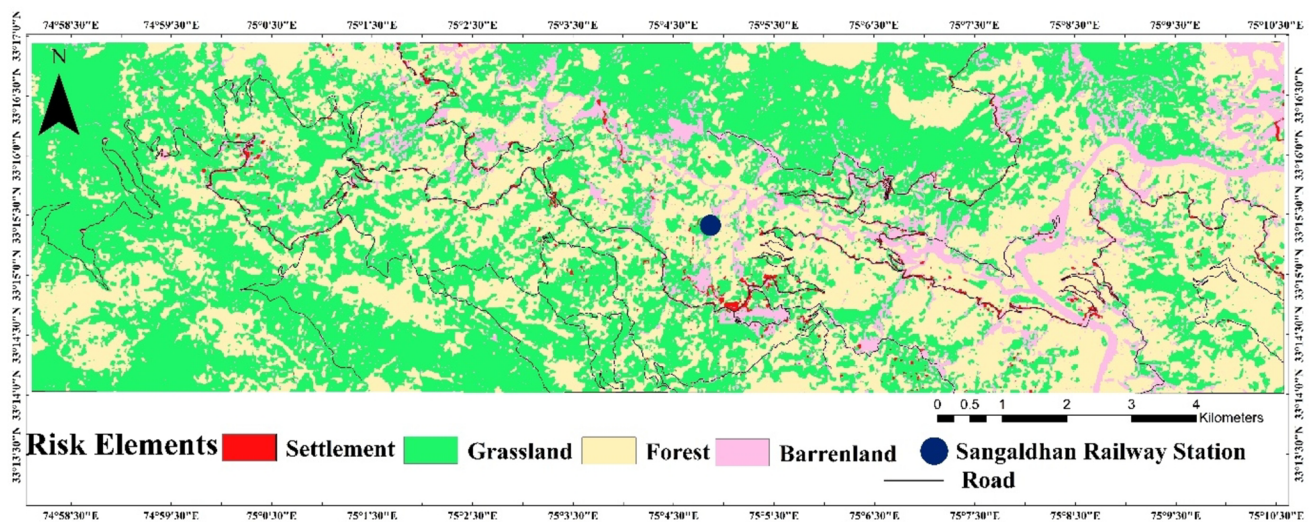


Fig. 10 Elements at risk due to landslide vulnerability of study area

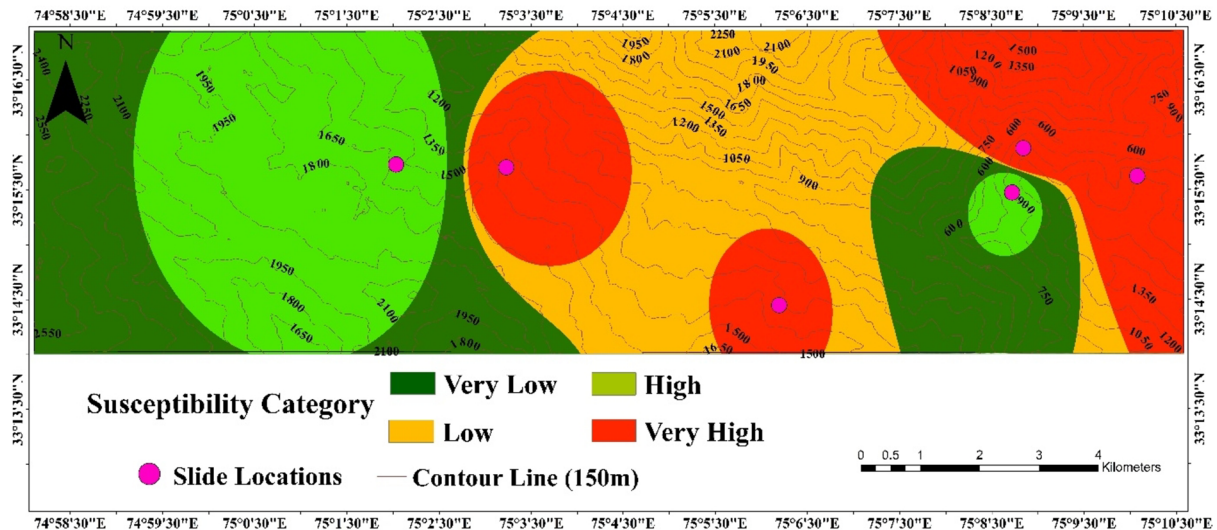


Fig. 11 LPI based landslide susceptibility zonation map for study area

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose. We know of no conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

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