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ORIGINAL ARTICLE

Stability assessment of Himalayan road cut slopes along National Highway 58, India

T. Siddique[1,2] · S. P. Pradhan[1] · V. Vishal[3] · M. E. A. Mondal[2] · T. N. Singh[3]

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Abstract Himalaya is one of the most tectonically and seismically active mountain chains in the world having complex geological and geotechnical conditions. The Himalayan region experiences frequent slope failure posed due to various natural and anthropogenic causes. Slope instability issues have consequent effects on the socio-economic development of the people and the region in a large scale. In the present study, stability analysis of vulnerable road cut slopes along NH-58 from Rishikesh to Devprayag in the Lesser Himalayas has been conducted. Critical slopes were identified by considering the geological and the geotechnical complexities within the region. Rock mass characterisation techniques have been employed for slope stability assessment. Rock mass rating (RMR), slope mass rating (SMR) and continuous slope mass rating (CSMR) methods have been applied to evaluate different stability levels of rock mass along the highway. Spatial variation of stability classes using RMR, SMR and CSMR techniques has been analysed on geographic information system (GIS) tool. Kinematic analysis technique was also employed to identify the different modes of structurally controlled failures in jointed rock mass. Accordingly remedial measures have been suggested to improve slope stability.

✉ S. P. Pradhan
sppradhanfes@iitr.ac.in

[1] Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee 247667, Uttarakhand, India

[2] Department of Geology, Aligarh Muslim University, Aligarh 202002, India

[3] Department of Earth Sciences, Indian Institute of Technology Bombay, Mumbai 400076, India

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Introduction

The network of roads including the national and state highways plays a vital role in socio-economic development and promotes the economy, more prominently in case of a mountainous region. Tourists, pilgrims and people residing in the Himalayan region are under constant threat of natural hazards and disasters like landslides, floods, earthquakes. Several such hazards are interlinked with each other, and the impact has been accelerated by locational elements such as height, slope, flowing river bodies. Infrastructure development in the Himalayan region is one of the major challenging tasks among geoscientists, engineers, constructors, planners, authorities and administration due to complex geomorphology and active tectonics. In recent times, landslide problems in the Himalayan region have been escalated due to infrastructure developmental activities particularly by road widening and hydropower projects (Singh et al. 2010). Large-scale slope failures and associated problems are very common in the region and need immediate evaluation and effective treatment to reduce inconvenience along transportation corridors and to mitigate damage of property and loss of lives. Himalayan rock slopes are inherently dissected by several sets of discontinuities and the non-scientific design of cut slopes further exposes new rock surfaces which act as avenues for slope failures (Singh et al. 2008). Mass movements in the Himalayan region are scale dependent from massive extension of whole mountain, failure of small peaks to smallest slope failure (Shroder and Bishop 1998). Due to large number of landslide causative factors, landslide prediction is very complex (Aghdam et al. 2017). Highly complex and intensely dynamic geomorphological, geometrical, meteorological, geological and geotechnical factors in the region need careful comprehensive evaluation for better understanding of underlying slope failure mechanism. These factors guide or control the equilibrium of the slopes, and any triggering factor like heavy rainfall, seismicity and unplanned excavation can cause disequilibrium leading to slope failure. Natural slopes become more vulnerable to failures when converted into cut slopes by human intervention for the purpose of transportation work, construction of dams, bridges, tunnels and other civil engineering structures (Vishal et al. 2010; Das et al. 2010). The vibration induced due to poor blasting during road construction and treatment stages causes widening of fractures and activation of small faults within the rock mass which lead to the instability of slopes. Unplanned excavations of hill-cut slopes reduce the stability of slopes (Umrao et al. 2011; Rentala and Satyam 2011). The consequences of slope failure can be very harmful when men and heavy earth-moving machines come close to unstable zone (Singh and Monjezi 2000). In the Himalayas, subtle variations in lithology and adverse orientation of discontinuities cause rock slope failures and some domains are so inevitable that practical remedial measures are sometimes quite ineffective and extremely costly (Ghosh et al. 2014). Demarcation and mitigation of landslide-prone areas in a region are very crucial for future planning and effective developmental activities (Ramesh and Anbazhagan 2015). Slope stability assessment in the Himalayan region needs extra care in consideration of highly variable and probable exogenic and endogenic factors which govern slope stability. In such complex regions, detailed field investigations, in-depth understanding of underlying mechanisms guiding slope failures and sound geotechnical assessment are the prerequisites for better understanding and insight to the problem. Adverse natural and anthropogenic factors have prompted large-scale slope failures along road cut slopes that provoked huge destructions to life and property. Uttarakhand Himalayas provides a reasonable insight into the environmental fragility of slopes, particularly in the areas traversed by major and minor tectonic structures (Sati et al. 2011). Uttarakhand Himalayan belt is tectonically sensitive and fragile terrain which poses frequent disasters in the region (Dudeja et al. 2017). Intensely devastating disaster of June 2013 in the Kedarnath valley of Uttarakhand was triggered due to flash floods, and these consequently triggered large-scale landslides in the region (Vishal et al. 2017). Deformed, weathered and fragile rocks in Lesser Himalaya are often vulnerable under natural and anthropogenic factors (Singh et al. 2017). From many decades, it has been noted that landslides in the Himalayan region occur frequently during and just after monsoon. However, improper blasting in road widening activities causes major landslides in dry season as well. Slope failure along NH-58 occurred mostly where road widening projects are either ongoing or completed (Sati et al. 2011). Mondal et al. (2016b) suggested that proper management, use of efficient scientific techniques, fractional and controlled blasting must be done to achieve better safety and economics during excavation. Rock mass in the region contains numerous sets of adversely oriented discontinuities which intersect to form blocks of varying sizes that are highly susceptible to sliding and falling. To improve landslide hazard assessment and for understanding landslide behaviour, observations of typical landslides over a long time period are necessary (Shang et al. 2017). To endeavour over rapid mass wasting problems in the Himalayan region, slope stability investigations should routinely performed. This forms an important component of risk evaluation posed due to the mass wasting phenomena. During preliminary phases of investigation, rock mass classification systems can be employed to identify the vulnerable zones of failure (Mondal et al. 2016a). The prime objective of all rock mass classification systems is to quantify the intrinsic properties of rock mass based on past experience and to investigate how external loading conditions acting on a rock mass may influence its behaviour (Milne et al. 1998). Rock mass classification system is a realistic means to provide comprehensive understanding of the material as applicable to field conditions. Such rating systems are employed to determine the quality of rock mass, to pre-design excavation and other processes required in tunnelling and underground rock engineering (Aksoy 2008). Rock mass rating (RMR) system was developed by Bieniawski (1973), and by experience and comprehensive notion over years it has been modified many times (Bieniawski 1974, 1975, 1976, 1989). RMR is a rating-based classification method in which ratings have been given to different parameters influencing the stability of rock mass and their algebraic sum define the quality of rock mass. Due to large range of ratings and lack of quantitative description for orientation parameters in RMR system, it is very difficult to assess stability of rock slopes with appreciable accuracy. However, detailed quantitative consideration of orientation parameter in slope mass rating (SMR) proposed by Romana (1985) makes it a much reliable tool to evaluate slope stability grade of jointed rock mass. SMR is one of the most widely used tools to understand the rock mass behaviour in slopes (Pradhan et al. 2011). Sarkar et al. (2012b) evaluated 50 slopes along road cut slopes in Garhwal Himalayas using rock mass rating (RMR), slope mass rating (SMR) and geological strength index (GSI). Sarkar et al. (2016) applied continuous slope mass rating and kinematic analysis techniques to identify different stability levels and potential structurally controlled failures along National Highway 22 in Himachal Pradesh. In and around India, ample research work have been done to evaluate stability of slopes in varying geological and geotechnical and climatic conditions by conventional rock mass characterisation, kinematic and advanced numerical simulation tools (Anbalagan et al. 1992; Anbazhagan et al. 2017; Kafle 2010; Mahanta et al. 2016; Naithani 2007; Pradhan et al. 2015; Ramesh et al. 2017; Regmi et al. 2016; Sarkar et al. 2012a; Siddique et al. 2015; Singh and Tamrakar 2017; Sharma et al. 2017; Umrao etal. 2011; Vishal et al. 2015; Verma et al. 2016). Such robust techniques to evaluate stability of slopes had gain immense attraction of researchers. In the present study, an attempt has been made to assess the stability of hill-cut slopes and to identify and evaluate the vulnerable slopes along NH-58 from Rishikesh to Devprayag using RMR, SMR and CSMR methods. Many structurally controlled failures at distinct locations were observed during field survey, and detailed assessment was conducted by kinematic analysis. The results obtained from distinct rock mass classification methods were corroborated with kinematic analysis.

Study area

In order to identify and characterise the slope stability conditions, a field survey was carried out in parts of Garhwal Himalayas along NH-58 from Rishikesh to Devprayag in Uttarakhand, India. It is a significant route connecting the Indo-Gangetic plains to the hilly regions. This route is one of the important pathways and contains many stopovers for tourists and pilgrims. Every year this highway experiences huge traffic due to massive inflow of pilgrims during March to August. In comparison with Indian subcontinent, the study area witnesses mild summers (March–May) with maximum temperature up to 40 °C and minimum up to 7 °C. Temperature falls significantly during monsoon (July–September), and the area experiences extensive rainfall. However, winters (November–February) are quite cold during which temperature falls below 0 °C. Irrespective of seasonal variations, days are warmer and nights are bit cooler which significantly accelerate chemical weathering phenomena. According to Geological Survey of India, annual precipitation in the area may range from 1000 to 2000 mm, which pose instability to the slopes.

The Himalayan orogen forms 2500-km-long and 250-km-wide arc along leading margin of India Plate and the Higher, Lesser and Sub-Himalaya are thus thrust slices of old Indian shield that have stacked over one another (Ghosh et al. 2016). The Lesser Himalayan ranges lies between the Greater Himalayas and the Siwalik ranges, and bounded by the Main Central Thrust (MCT) and Main Boundary Thrust (MBT), respectively. Most parts of this terrain comprise of Precambrian rocks older than 542 Ma in age and few are younger up to Eocene. Lesser Himalayan sequence includes metasedimentary rocks, metavolcanic rocks and augen gneiss (Frank et al. 1995; DeCelles et al. 1998; Upreti 1999). This sequence had experienced multiple phases of contraction (Schelling and Arita 1991). The geological setting of Kumaon and Garhwal Himalaya has been studied over many decades (Middlemiss 1885; Auden 1935; Heim and Gansser 1939; Rupke 1974; Valdiya 1980 and 1995; Richards et al. 2005). Heim and Gansser (1939) divided the geology of the Himalaya in different parts such as the Sub-Himalayan sequence, the Lesser Himalayan sequence, the Greater Himalayan crystalline and the Tethyan Himalayan sequence. Further the lesser Himalayas can be divided into two different broad units, i.e. inner and outer Lesser Himalayan sequence (Ahmad et al. 2000). According to Valdiya (1980), the outer Lesser Himalaya majorly comprises of Chakrata formation (mostly sandstone and siltstone); Rautgara formation (mostly sandstone and quartzite); Mandali formation (mostly slates and phyllite); Chandpur formation (mostly phyllite); Nagthat formation (mostly quartzite); Blaini formation of early Proterozoic (mostly siltstone and slates); Krol formation of late Proterozoic (mostly limestone); Tal formation of early Cambrian (mostly sandstone); Bansi and Subathu formation of Cretaceous to Paleocene (mostly shelly limestone and sandstone); Ramgarh group (mostly granitic, phyllite and siltstone). There are six major synclines in the Lesser Himalayan sequence (Nanital, Garhwal, Mussoorie, Naglidhar, Pachmunda and Krol syncline). Study area lies in Garhwal syncline of outer Lesser Himalayas along NH-58, from Rishikesh to Devprayag. Thirty-five critical slopes were identified along the route which is susceptible to slope instabilities. The lithologies encountered at different slopes are given in Table 1. Digital elevation model was prepared, and the studied locations were marked (Fig. 1).

Methodology

The evaluation of slope stability by rock mass classification tool is widely practiced by many researchers. It provides quick, efficient and reliable assessment during preliminary stages. The primary objectives of applying rock mass classification systems to slopes are to identify and evaluate parameters affecting stability of rock mass, to improve the quality of proposed site in terms of stability, to provide quantitative information for better, economic and efficient engineering design. Rock mass classification systems are

Table 1 Lithology and corresponding geological formations at different locations

Location	Lithology	Geological formation	Location	Lithology	Geological formation
S1	Limestone	Krol	S19	Sandstone	Tal
S2	Sandstone	Tal	S20	Sandstone	Tal
S3	Sandstone	Tal	S21	Sandstone	Tal
S4	Limestone	Krol	S22	Slate	Tal
S5	Sandstone	Blaini	S23	Sandstone	Tal
S6	Sandstone	Blaini	S24	Sandstone	Tal
S7	Slate	Blaini	S25	Limestone	Krol
S8	Phyllite	Blaini	S26	Limestone	Krol
S9	Sandstone	Tal	S27	Limestone	Krol
S10	Sandstone	Tal	S28	Sandstone	Chakrata
S11	Quartzite	Tal	S29	Sandstone	Chakrata
S12	Quartzite	Tal	S30	Sandstone	Chakrata
S13	Sandstone	Ramgarh	S31	Sandstone	Chakrata
S14	Slate	Ramgarh	S32	Sandstone	Chakrata
S15	Sandstone	Ramgarh	S33	Sandstone	Chakrata
S16	Sandstone	Ramgarh	S34	Sandstone	Chandpur
S17	Sandstone	Ramgarh	S35	Phyllite	Chandpur
S18	Sandstone	Ramgarh			

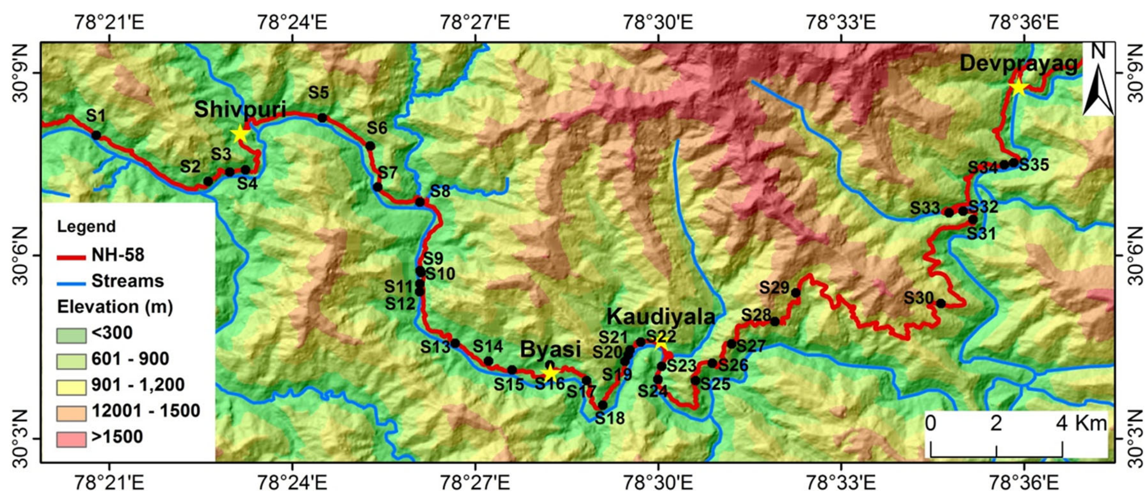

Fig. 1 Digital elevation model showing topography of the region and investigated slopes along NH-58 from Rishikesh to Devprayag

universal communication system for explorers, designers and constructors (Tomás et al. 2007). These classification systems are useful means for the assessment for the stability potential based on most inherent and structural parameters (Taherniya et al. 2014). These systems form the backbone of empirical design approach which relates the experiences encountered at previous projects to the conditions anticipated at the proposed site (Bieniawski 1990). Pantelidis (2009) discussed the major differences, similarities, factors involved, type of failure considered for evaluation of rock mass and reliability of different schemes for discrete purposes. The main advantage of rock mass classification systems is that they are a simple and effective way of representing quality of rock mass and of encapsulating precedent practice (Harrison and Hudson 2000). Many rock mass classification systems have been developed and modified over years by various researchers which are frequently applied for different purposes: to determine strength and deformability of rock mass, slope stability assessment, in mining and tunnelling operations, dam foundations. Some classification schemes have been developed originally by performing extensive laboratory and field investigation, and some have been developed from original proposals. With time and broader experience in the field of rock mechanics and slope stability evaluation, refinement in parameters and their relative weighage have been incorporated. Some widely used classification systems have been listed in Table 2. Hoek (2000)

Table 2 Summary of the existing rock mass classification schemes

Name of the systems (abbreviations)	Authors and year of development	Applications
–	Ritter (1879)	Tunnels
Rock load	Terzaghi (1946)	Tunnels
Stand-up time	Lauffer (1958)	Tunnels
Rock quality designation (RQD)	Deere (1963)	General
New Austrian tunnelling method (NATM)	Rabcewicz (1964)	Tunnels
Rock classification for rock mechanics purposes	Patching and Coates (1968)	General
Rock structure rating (RSR)	Wickham et al. (1972)	Small Tunnels
Rock mass rating (RMR)	Bieniawski (1973)	Tunnels
Rock tunnelling quality index (Q)	Barton et al. (1974)	Tunnels
Size-strength classification	Franklin (1975)	Tunnels
Mining rock mass rating (M-RMR)	Laubscher (1977)	Mines
Geodurability classification	Olivier (1979)	Tunnels
Rock mass strength (RMS)	Selby (1980)	Cuttings
Unified rock classification system (URCS)	Williamson (1984)	General
Basic geotechnical description (BGD)	ISRM (1981)	General
Excavability index (*N*)	Kristen (1982)	Excavation
Modified basic RMR (MBR)	Kendorski et al. (1983)	Mines
Simplified rock mass rating (R)	Brook and Dharmaratne (1985)	Mines
Slope mass rating (SMR)	Romana (1985)	Cuttings
CMRS geomechanics classification	Venkateshwarlu (1986)	Mines
Slope rock mass rating (SRMR)	Robertson (1988)	Cuttings
Mining rock mass rating (M-RMR)	Haines and Terbrugge (1991)	Mines
Modified slope mass rating	Anbalagan et al. (1992)	Cuttings
Ramamurthy and Arora classification	Ramamurthy and Arora (1993)	General
Coal mine roof rating (CMRR)	Molinda and Mark (1994)	Mines
Index of rock mass basic quality (BQ)	NSCGPRC (1994)	Cuttings
Natural slope methodology (NSM)	Shuk (1994)	Mines
Chinese slope mass rating (CSMR)	Chen (1995)	Cuttings
Rock mass number (*N*)	Goel et al. (1995)	Tunnels
Geological strength index (GSI)	Hoek et al. (1995)	General
Rock mass index (RMi)	Palmström (1995)	General
Modified rock mass rating (M-RMR)	Ünal (1996)	Mines
Rock slope deterioration assessment (RDA)	Nicholson and Hencher (1997)	Cuttings
Slope stability probability classification (SSPC)	Hack (1998)	Cuttings
In situ rock mass rating (IRMR)	Laubscher and Jakubec (2000)	General
Rock mass classification for coal measures (RMCR)	Yasar (2001)	Mines
Dam mass rating (DMR)	Romana (2003)	Dams
Modified rock mass classification	Şen and Sadagah (2003)	General
Volcanic rock face safety rating (VRFSR)	Singh and Connolly (2003)	Cuttings
Slope failure index (SFi)	Jeong et al. (2007)	Cuttings
Continuous slope mass rating	Tomás et al. (2007)	Cuttings
Rock mass fabric indices (*F*)	Tzamos and Sofianos (2007)	Tunnels
Korean slope mass rating (KSMR)	Song et al. (2008)	Cuttings
Modified slope mass rating (M-SMR)	Rahim et al. (2009)	Cuttings
Hazard index (HI)	Pantelidis (2010)	Cuttings
Slope stability rating (SSR)	Taheri and Tani (2010).	Cuttings
Fuzzy slope mass rating (FSMR)	Daftaribesheli et al. (2011)	Cuttings
Graphical slope mass rating (GSMR)	Tomás et al. (2012)	Cuttings
New slope mass rating (NSMR)	Singh et al. (2013)	Cuttings
New priority rating system (NPRS)	Wong (2013)	Cuttings

Table 2 continued

Name of the systems (abbreviations)	Authors and year of development	Applications
Rock mass quality rating (RMQR)	Aydan et al. (2014)	General
Slope quality rating (SQR)	Fereidooni et al. (2015)	Cuttings
Slope quality index (SQI)	Pinheiro et al. (2015)	Cuttings
Continuous rock mass rating	Rad et al. (2015)	General
Rock engineering system for carbonate rocks	Andriani and Praise (2017)	General

ISRM international society of rock mechanics, *CMRS* central mining research station, *NSCGPRC* national standards compilation group of the People's Republic of China

suggested that different classification system emphasise on different parameters, and it is often recommended that at least two methods should be used when classifying a rock mass.

Rock mass rating (RMR)

Rock mass rating (RMR), also named as the geomechanics classification system was introduced by Bieniawski (1973) at the South African Council of Scientific and Industrial Research (CSIR) on the basis of 49 unpublished case histories. RMR involves six parameters to characterise the rock mass, viz. unconfined compressive strength of intact rock (UCS), rock quality designation index (RQD), mean discontinuity spacing, discontinuity conditions, groundwater conditions and adjustment factor related to discontinuity orientation. These parameters have been divided into several classes, and each class has particular rating. Rating of each parameter is given on the basis of obtained laboratory results and prevailing field conditions. Arithmetic sum of rating provides RMR value which gives an idea about rock mass quality. RMR is widely applicable in many rock engineering projects like tunnelling, dams, slope stability. Several major modifications have been made over the years with availability of more data, broader experience and in-depth understanding about slope failure processes, i.e. reduction of parameters from 8 to 6 by Bieniawski (1974); adjustment of ratings and reduction of support measures by Bieniawski (1975); on the basis of 64 case histories modifications have been made in class boundaries by Bieniawski (1976); and on the basis of more than 268 case histories for tunnels, mines, slopes and foundations by Bieniawski (1989). Therefore, it is very important to quote the version of RMR system used for the stability assessment. In a latest version of RMR (1989), in case of slopes rating adjustments for discontinuity orientations were classified into very favourable (0), favourable (− 5), fair (− 25), unfavourable (− 50) and very unfavourable\ (− 60). The limitation of the system is the scope for large differences in ratings of each category, and lack of guidelines to determine the rating increases the subjectivity of the system. Any diminutive misguide in defining the category for orientation factor may mislead the final results and may give imprecise stability grade of the rock mass.

Slope mass rating (SMR)

Romana (1985) recognised and perceived the significance of quantification for relative orientation of slope with respect to discontinuities present in the rock mass. He quantified orientation parameters and designed slope mass rating (SMR) for explicit assessment of stability grade for slopes. By vast experiences and availability of more data, several modifications have been made in the SMR system by Romana (1991); Anbalagan et al. 1992; Romana 1993, 1995; Romana et al. 2001, 2003. SMR is most extended and applied to rocky slopes due to its ease and exhaustive, well established and quantitative description of correction factors (Tomás et al. 2007). SMR is computed from $\mathrm{RMR_{Basic}}$ (algebraic sum of ratings of only first five parameters) and adjustment factors F_1, F_2, F_3 and F_4.

$$\mathrm{SMR} = \mathrm{RMR_{Basic}} + (F_1 \cdot F_2 \cdot F_3) + F_4$$

where F_1, F_2, F_3 are factorial adjustment factors depending upon relative orientation of slope and discontinuity for different mode of structurally controlled failures and F_4 is related to method of excavation.

F_1 depends upon parallelism between dip direction of discontinuity and slope face which is calculated using apparent dip direction of slope and discontinuity causing planar and toppling mode of failure. While for wedge mode apparent dip direction of the slope and the trend of the line formed by the intersection of two discontinuities forming wedge failure are considered for calculation of F_1.

F_2 refers to dip angle of discontinuity in planar and wedge mode of failure, while for toppling mode it remains 1. F_3 is related to the relationship between amount of slope inclination and dip amount of discontinuity which is computed using amount of inclination of slope face and dip amount of discontinuity causing planar and toppling failure. While for wedge mode of failure, slope inclination and amount of plunge formed by the intersection of two discontinuities forming wedge are considered for calculation of F_2.

F_4 depends upon method of excavation which has been fixed empirically (Romana et al. 2003).

Adjustment factors related to orientation are calculated using discontinuity orientation data. However, in case of multiple sets of discontinuities most critical discontinuity set is selected for computation of SMR. However, one must be careful while considering most vulnerable discontinuity, it should be well distributed throughout the slope. SMR classes, description, stability grade, failures and support required can be determined from total SMR value for different modes of failure. To design effective remedial measures of a slope, detailed fieldwork and sound engineering sense are prerequisites. SMR recommendations provide a first approximation during initial stages of the project (Romana et al. 2015). Zheng et al. (2016) have given brief overview on rock mass classification particularly on slope mass rating and its theoretical defects.

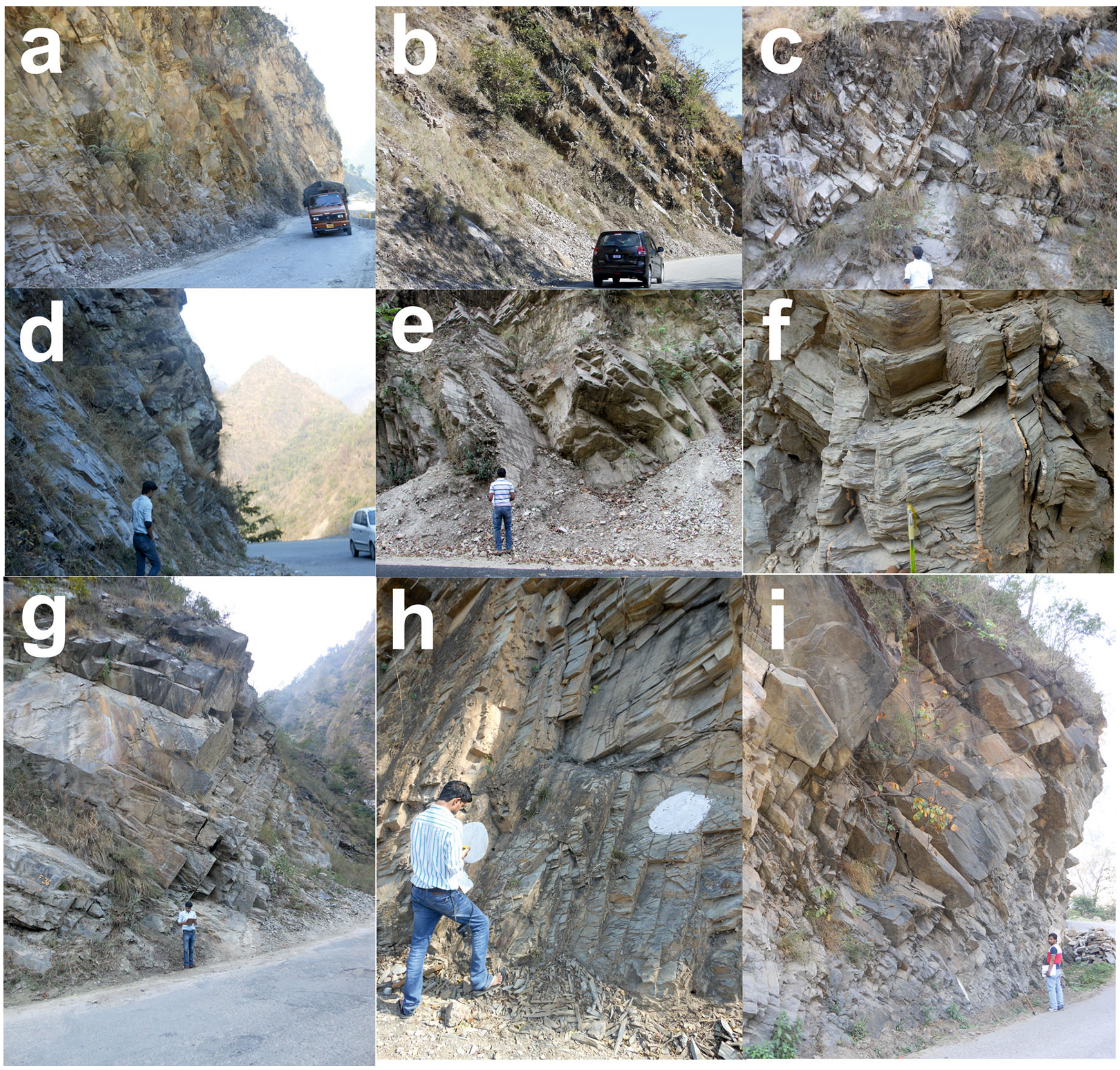

Fig. 2 Field photographs depicting conditions of rock mass **a** highly persistent discontinuities with large overhang (Location 12); **b** discontinuities forming planar failure (Location 10); **c** blocky rock mass forming wedge failure (Location 11); **d** unstable blocks giving rise to planar failure conditions (Location 10); **e** blocky rock mass forming wedge mode of failure and small chunks or blocks fallen at the toe of slope (Location 13); **f** intensely deformed rock mass having secondary filling of silica (Location 35); **g** daylight conditions forming planar mode of failure and discontinuities intersecting forming wedge mode of failure with significant signs of chemical alteration in rock mass (Location 19); **h** closely spaced joints and foliation in phyllite forming small chunks or blocks which occasionally fall or slide along cut slope(Location 8); **i** blocky appearance of rock mass due to intersection of discontinuities with large overhang (Location 5)

Table 3 Uniaxial compressive of intact rock samples from discrete locations

Location	UCS (MPa)			Location	UCS (MPa)			Location	UCS (MPa)		
S1	49	45	43	S13	46	43	47	S25	36	34	37
S2	50	43	46	S14	16	19	22	S26	39	38	42
S3	47	44	49	S15	51	45	47	S27	38	39	41
S4	37	45	43	S16	45	46	49	S28	42	47	44
S5	40	43	48	S17	46	51	44	S29	43	48	42
S6	49	47	41	S18	43	47	46	S30	47	41	45
S7	20	19	23	S19	38	42	40	S31	44	42	47
S8	21	17	23	S20	37	43	41	S32	38	42	40
S9	43	48	46	S21	33	40	37	S33	40	43	46
S10	43	45	47	S22	12	13	16	S34	17	21	19
S11	73	87	78	S23	40	44	46	S35	22	15	18
S12	69	76	77	S24	43	48	42				

Continuous slope mass rating (CSMR)

By incorporating continuous functions to Romana's SMR method, continuous slope mass rating was proposed by Tomás et al. (2007) in order to get more precise evaluation of stability grades. Many instances, it has been noticed that SMR values slightly deviates from real-field conditions. This may occur during computation of adjustment factors when values lies at border of pre-defined class intervals. However, consideration of continuous functions had suppressed this problem. Due to which CSMR method is the most robust technique while dealing with assessment of slope stability. Adjustment factors using continuous functions can be calculated by following equations:

$$F_1 = \frac{16}{25} - \frac{3}{500} \arctan\left(\frac{1}{10}(|A| - 17)\right)$$

where A is |αj − αs| for planar failure, |αj − αs − 180°| for toppling failure and |αi − αs| for wedge failure

$$F_2 = \frac{9}{16} + \frac{1}{195} \arctan\left(\frac{17}{100}B - 5\right)$$

where B is βj for planar failure and βi for wedge failure, while F_2 remains 1 for toppling mode of failure.

$$F_3 = -30 + \frac{1}{3} \arctan\ C \ \text{(For Planar and Wedge Failure)}$$

where C is βj − βs for planar failure, βi − βs for wedge failure and βj − βs for toppling failure

$$F_3 = -13 - \frac{1}{7} \arctan\ (C - 120) \ \text{(For Toppling Failure)}$$

Note that for all above equations, arctangent will be in degrees.

αs is dip direction of slope, αj is dip direction of joint, βs is dip amount of slope, βj is dip amount of joint, αi is dip direction of line formed by the intersection of two discontinuities and βi is amount of plunge of line formed by the intersection of two discontinuities.

Kinematic analysis

Kinematics also called as 'geometry of the motion'. It is the branch of classical mechanics that evaluate the motion of point/object/body irrespective to its cause of motion. It is purely geometric evaluation of slope to identify potential for different modes of structurally controlled rock slope failures due to unfavourably oriented discontinuities within the rock mass. Qualitative assessment of various

Table 4 Rock quality designation of road cut slopes along NH-58, Rishikesh–Devprayag

Location	RQD%	Location	RQD%	Location	RQD%	Location	RQD%
S1	58.15	S10	56.48	S19	73.71	S28	48.30
S2	49.78	S11	72.82	S20	67.54	S29	80.80
S3	48.94	S12	35.31	S21	74.16	S30	66.28
S4	73.73	S13	58.02	S22	47.15	S31	65.13
S5	72.32	S14	16.94	S23	69.68	S32	44.52
S6	73.21	S15	73.81	S24	66.61	S33	43.46
S7	37.23	S16	70.97	S25	61.60	S34	73.89
S8	22.05	S17	60.91	S26	39.16	S35	32.12
S9	78.83	S18	58.96	S27	61.98		

structurally controlled failures like planar, toppling and wedge mode can be made by this method. Angle of internal friction, orientation of pertaining discontinuities and slopes are the inputs required for the kinematic evaluation. Angular relationships between structural discontinuities in rocks and the gradient and aspect of the topography define different modes of rock slope failures (Goodman and Bray 1976; Hoek and Bray 1981; Yoon et al. 2002). If the strike of discontinuity is nearly parallel (± 20°) to the trend of slope and dip of discontinuity is gentle than that of slope, then planar failure is likely to occur. If strike of discontinuity is nearly parallel (± 20°) to the trend of the slope but discontinuity is dipping steeply in opposite to that of slope direction, it will give rise to toppling failure mode

Table 5 Rock mass rating results of investigated road cut slopes

L	UCS	RQD	SD	CD					GW	RMR_b	AOF	Total RMR	Description of stability grade
				P	A	R	I	W					
S1	4	13	8	2	1	2	6	3	15	54	− 25	29	Poor
S2	4	8	8	2	4	2	6	3	15	52	− 25	27	Poor
S3	4	8	8	1	1	5	6	5	15	53	− 25	28	Poor
S4	4	13	10	1	1	3	2	4	15	53	− 5	48	Fair
S5	4	13	10	1	1	2	6	5	15	57	− 25	32	Poor
S6	4	13	10	1	1	3	6	1	15	54	− 25	29	Poor
S7	2	8	10	1	1	1	2	5	15	45	− 25	20	Very poor
S8	2	3	8	2	4	3	6	5	15	48	− 25	23	Very poor
S9	4	17	10	2	1	2	6	5	15	62	− 25	37	Poor
S10	4	13	15	2	1	1	6	5	15	62	− 25	37	Poor
S11	7	13	10	2	1	4	6	5	15	63	− 25	38	Poor
S12	7	8	8	1	1	2	6	4	15	52	− 25	27	Poor
S13	4	13	8	1	1	2	6	5	15	55	− 25	30	Poor
S14	2	3	8	1	1	2	6	5	15	43	− 5	38	Poor
S15	4	13	10	0	4	1	6	5	15	58	− 25	33	Poor
S16	4	13	10	2	1	2	6	5	15	58	− 25	33	Poor
S17	4	13	10	1	1	3	4	5	15	56	− 5	51	Fair
S18	4	13	8	1	1	1	2	3	15	48	− 25	23	Poor
S19	4	13	10	1	1	1	6	1	10	47	− 25	22	Poor
S20	4	13	10	2	1	2	6	5	15	58	− 25	33	Poor
S21	4	13	10	0	1	1	6	5	0	40	− 25	15	Very poor
S22	2	8	8	2	1	1	6	4	15	36	− 25	11	Very poor
S23	4	13	10	1	1	2	4	5	15	55	− 25	30	Poor
S24	4	13	10	0	1	3	6	1	15	53	− 25	28	Poor
S25	4	13	8	1	1	2	6	1	10	46	− 25	21	Poor
S26	4	8	8	2	1	1	6	5	15	50	− 25	25	Poor
S27	4	13	8	1	1	3	6	3	15	54	− 25	29	Poor
S28	4	8	8	1	1	2	6	1	15	46	− 25	21	Poor
S29	4	17	10	0	1	2	6	5	15	60	− 25	35	Poor
S30	4	13	10	0	1	3	6	5	15	57	− 25	32	Poor
S31	4	13	10	1	1	3	6	4	15	57	− 25	32	Poor
S32	4	8	8	1	1	3	6	5	10	46	− 25	21	Poor
S33	4	8	8	1	1	3	6	5	15	51	− 25	26	Poor
S34	2	13	10	1	1	3	4	5	15	54	− 25	29	Poor
S35	2	8	8	1	1	3	2	1	15	41	− 25	16	Very poor

L location number, *UCS* uniaxial compressive strength of intact rock material, *RQD* rock quality designation, *SD* spacing of discontinuities, *CD* conditions of discontinuities, *P* persistence, *A* aperture, *R* roughness, *I* infilling, *W* weathering, *GW* groundwater conditions, RMR_b, RMR_{basic}, *AOF*; adjustment for discontinuity orientation factor

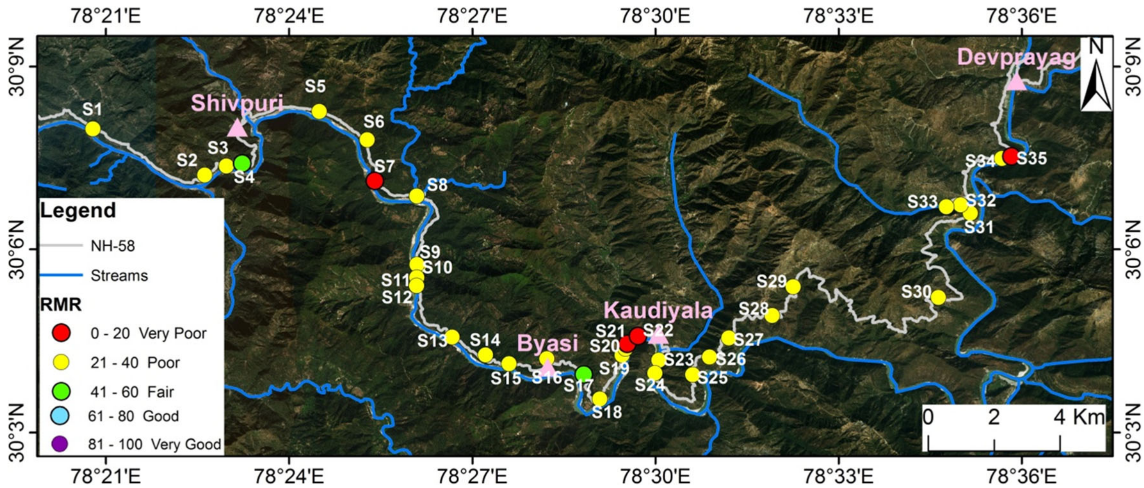

Fig. 3 Spatial distribution of RMR stability classes along NH-58, Rishikesh–Devprayag

conditions. Wedge failure is likely to occur when two discontinuity individually not forming any failure but they intersect in such a way that line formed by intersection daylight into slope face, i.e. amount of plunge is lesser than angle of slope provided the plunge of the intersection should also exceed the friction angle. Such geometric evaluation provided comprehensive understanding of various structurally controlled failures during field survey and revealed possible mode of failures at discrete locations in the study region.

Results and discussion

Detailed field investigations were conducted, and 35 vulnerable rock cut slopes along NH-58 were selected for detailed evaluation. The rock slopes belong to Garhwal syncline of Lesser Himalaya. Many unstable slopes have been reported during field survey which seems to be vulnerable for different structurally controlled failures in outlook (Fig. 2).

Rock masses along the highway have been intensely jointed, and generally 3–4 sets of joints have been reported from discrete locations. Detailed geotechnical mapping pertinent to slope stability was recorded during field survey. Discontinuity data influencing slope stability have been carefully examined during field surveys, and rock slope stability assessment was done using rock mass classification tools (RMR, SMR and CSMR). Representative rock samples were collected for laboratory test for evaluation of mechanical properties of intact rock. Tests were performed by extracting NX-sized cores (54.7 mm in diameter) to calculate uniaxial compressive strength of intact rock material (Table 3) as per to the specifications given by International Society of Rock Mechanics (ISRM 1978), and accordingly rock masses have been rated by using RMR method.

Rock quality designation (RQD) was developed by Deere (1963) which gives quantitative estimation of quality of rock mass from drill core logs. RQD is core recovery that relies upon fracture frequency and softening of rock mass encountered during drilling. However, if the core drilling is not available, RQD can be estimated by volumetric joint count (Jv) using empirical relationship (Eq. 1) suggested by Palmstrom (1982). Jv was introduced by Palmstrom (1974) which is a measure of number of joints present within a unit volume of rock mass (Eq. 2). RQD% has been calculated for all studied locations by using Eq. 1 (Table 4).

$$\mathrm{RQD} = 115 - 3.3\,\mathrm{Jv} \quad (1)$$

$$\mathrm{Jv} = 1/S1 + 1/S2 + 1/S3 + \cdots 1/Sn + \ \mathrm{Nr}/5\sqrt{\mathrm{A}} \quad (2)$$

where Jv is volumetric joint count$S1$, $S2$ and $S3$ are discontinuity spacing for set 1, set 2 and set 3, respectively$A$ is area in m^2Nr is the number of random set of discontinuities present in the rock mass.

Discontinuity spacing is perpendicular distance between two discontinuities which controls the size and shape of blocks in jointed rock mass and also influences permeability and seepage characteristics within the rock mass. Discontinuity spacing for each set has been measured in field with precision to assign rating in RMR system. Discontinuity conditions like persistence, aperture, roughness, infilling and weathering largely influence stability of rock mass. These parameters have been recorded carefully during field survey, and average values have been considered for rating. Seepage of groundwater within rock slopes usually takes place through discontinuities present in the rock mass. It also affects water pressure and shear strength of the material. Hydrological properties were recorded in

Table 6 Slope mass rating results of investigated road cut slopes

Slope	RMR basic	Type of failure	F_1	F_2	F_3	F_4	SMR	Class	Grade
S1	54	W (J1–J3)	0.40	1.00	− 60.00	+ 10	40	IV	UN
S2	52	P (J1)	0.15	1.00	− 60.00	+ 10	53	III	PS
		T (J2)	0.70	1.00	− 25.00	+ 10	44	III	PS
S3	53	W (J1–J2)	0.70	1.00	− 60.00	+ 10	21	IV	UN
S4	53	W (J1–J2)	0.40	0.40	− 60.00	+ 8	51	III	PS
S5	57	P (J1)	1.00	0.85	− 60.00	+ 10	16	V	CU
		W (J1–J3)	1.00	0.85	− 60.00	+ 10	16	V	CU
S6	54	W (J1–J2)	0.85	1.00	− 60.00	+ 8	11	V	CU
S7	45	T (J1)	0.40	1.00	− 25.00	+ 8	43	III	PS
S8	48	P (F)	0.85	1.00	− 60.00	+ 10	7	V	CU
		W (F–J1)	0.15	1.00	− 60.00	+ 10	44	III	PS
S9	62	P (J1)	1.00	1.00	− 60.00	+ 10	12	V	CU
S10	62	W (J1–J3)	0.70	1.00	− 60.00	+ 10	30	IV	UN
S11	63	W (J1–J2)	1.00	1.00	− 60.00	+ 8	11	V	CU
S12	52	T (J2)	0.85	1.00	− 25.00	+ 8	39	IV	UN
S13	55	T (J2)	0.70	1.00	− 25.00	+ 10	47	III	PS
S14	43	P (J1)	0.15	1.00	− 60.00	+ 8	42	III	PS
S15	58	W (J1–J3)	0.70	1.00	− 60.00	+ 8	24	IV	UN
S16	58	W (J2–J3)	0.85	0.85	− 60.00	+ 10	25	IV	UN
S17	56	W (J1–J2)	0.15	1.00	− 50.00	+ 10	58	III	PS
S18	48	P (J1)	0.85	1.00	− 50.00	+ 10	15	V	CU
		W (J2–J4)	1.00	0.70	− 60.00	+ 10	16	V	CU
S19	47	P (J1)	0.40	0.85	− 60.00	+ 10	37	IV	UN
		W (J1–J3)	0.40	0.85	− 60.00	+ 10	37	IV	UN
S20	53	P (J3)	0.70	1.00	− 60.00	+ 10	26	IV	UN
S21	40	P (J3)	0.40	1.00	− 50.00	+ 10	30	IV	UN
		W (J1–J3)	0.15	0.85	− 60.00	+ 10	42	III	PS
S22	36	P (J2)	0.70	0.85	− 60.00	+ 10	10	V	CU
		W (F–J2)	0.15	0.70	− 60.00	+ 10	40	IV	UN
S23	55	P (J1)	0.70	1.00	− 60.00	+ 10	23	IV	UN
S24	48	P (J1)	0.85	0.85	− 60.00	+ 10	20	V	CU
S25	46	P (J2)	0.4	1.00	− 50.00	+ 8	34	IV	UN
		W (J1–J2)	0.15	1.00	− 60.00	+ 8	45	III	PS
S26	50	W (J1–J2)	0.85	1.00	− 60.00	+ 10	9	V	CU
S27	54	P	0.70	1.00	− 60.00	+ 10	22	IV	UN
		W (J1–J3)	0.15	1.00	− 60.00	+ 10	55	III	PS
S28	46	W (J1–J3)	0.70	0.85	− 60.00	+ 10	20	V	CU
S29	55	P (J1)	0.40	0.85	− 60.00	+ 10	48	III	PS
		W (J1–J2)	0.15	0.85	− 60.00	+ 8	60	III	PS
S30	57	P (J1)	1.00	1.00	− 60.00	+ 8	7	V	CU
S31	57	P (J1)	0.70	1.00	− 60.00	+ 10	25	IV	UN
		W (J1–J3)	0.70	0.85	− 60.00	+ 10	31	IV	UN
S32	57	P (J3)	0.40	1.00	− 60.00	+ 10	43	III	PS
		W (J1–J2)	0.85	1.00	− 60.00	+ 10	16	V	CU
S33	46	W (J1–J2)	0.7	0.85	− 60.00	+ 8	18	V	CU
S34	54	W (J2–J3)	0.15	1.00	− 60.00	+ 8	53	III	PS
S35	41	T (J2)	0.70	1.00	− 25.00	+ 10	33	IV	UN
		W (J3–J4)	0.40	0.40	− 60.00	+ 10	41	III	PS

P planar failure, *T* toppling failure, *W* wedge failure, *J* joint, *F* foliation, *CU* completely unstable, *UN* unstable, *PS* partially stable, F_1, F_2, F_3 are adjustment factors related to relative orientation of discontinuities and slope, F_4 adjustment factor for method of excavation

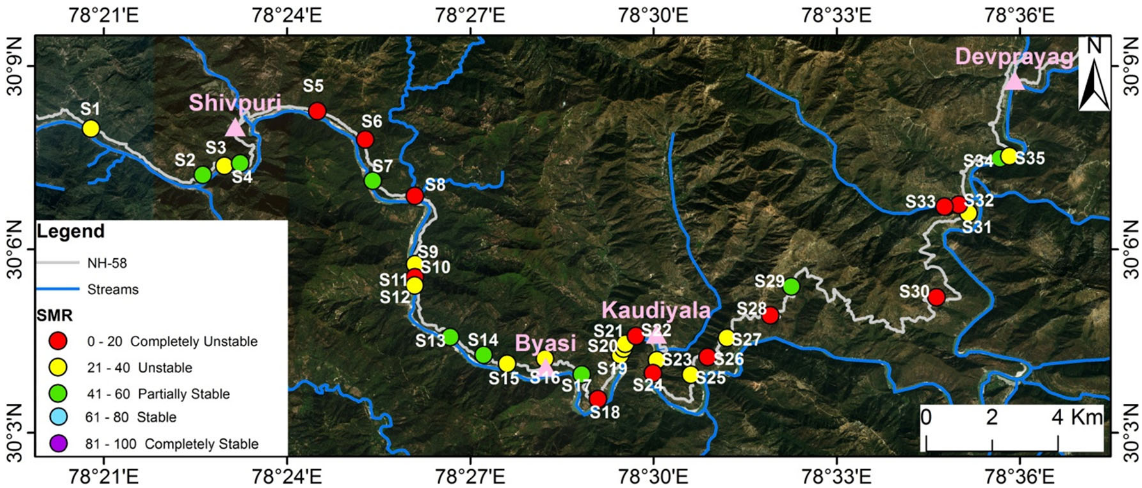

Fig. 4 Spatial distribution of SMR stability classes along NH-58, Rishikesh–Devprayag

the month of March when rock mass experiences least impact of rainwater. However, moist to flowing condition has been recorded at certain slopes during survey and from some slopes near Kaudiyala water flows round the indicating shallow water table. The discontinuities present in the rock mass are the avenues for movement of groundwater to the surface. Continuous discharge of groundwater is hampering quality of rock mass to a great extent. Such continuous seepage of groundwater causes softening of rock by forming clay material along joint planes which further act as lubricant for failure of rock mass. It also increases pore pressure which aggravates instability of slopes. Discontinuity orientation is one of the most guiding factors in controlling different modes of structurally controlled failures in jointed rock mass. Relative orientations of slope and discontinuities present in rock mass have been recorded during field survey. By stereographic projection of these planes, qualitative assessment has been made to determine favourability to failure to assign rating for orientation adjustment factor. Total RMR rating dictates the quality grade of rock mass which is the algebraic sum of ratings of all six parameters, viz. uniaxial compressive strength of intact rock material, RQD, spacing of discontinuities, conditions of discontinuities, groundwater conditions and adjustment for relative orientation of slope and discontinuities present (Table 5; Fig. 3). As discussed in previous section, orientation parameter in RMR method is completely subjective assessment. So, in conjunction with RMR method, SMR technique has been employed to reduce subjectivity in evaluation of stability because of qualitative assessment of orientation factor. Due to this reason, it is considered to be one of the most robust classification systems for the evaluation of slope stability. SMR is an adaptation of Bieniawski's RMR which includes RMR_{basic}, and some factorial adjustment factors (F_1, F_2 and F_3) have been calculated using orientation of slope face and the most vulnerable discontinuity set within the rock mass. On the basis of visual inspection, adjustment factor F_4 was determined carefully for every location. Total SMR values for different modes of failures have been calculated for each slope to determine stability grade of rock masses (Table 6; Fig. 4). Similarly, CSMR values have been calculated by using continuous functions of adjustment factors F_1, F_2 and F_3 to reduce ambiguity that arises due to values at the boundaries of class intervals (Table 7; Fig. 5). Among all CSMR is most suitable technique while dealing with slope stability due to much quantitative consideration of parameters influencing stability of slopes. In the study area, it has been observed that SMR values obtained for different slopes are slightly deviates from CSMR value which rise due to consideration of discrete and continuous functions in SMR and CSMR, respectively. Hence CSMR suppresses the results obtained by SMR method and undoubtedly CSMR values are much closer to real prevailing field condition. Rating results obtained especially by CSMR method classify different vulnerable sections into different grades, and such outcomes can be utilised by roadway and transportation sector to attain much safer design during road safety treatment. Different government and private agencies involved in roads and transportation development can focus on extremely hazardous slopes during road renovation projects. Implementation of these results on ground will reduce fatalities and accidents along the stretch posed due to landslides. Overall, it would lead to swift socio-economic development of the region along with smooth conduct of tourism activities.

Spatial stability analysis within study area has been shown in Figs. 4, 5 and 6 using GIS technology. RMR, SMR and CSMR values have been categorised into five

Table 7 Results of continuous slope mass rating

Slope	RMR basic	Type of failure	F_1	F_2	F_3	F_4	SMR	Class	Grade
S1	54	W (J1–J3)	0.54	0.96	− 59.05	+ 10	33	IV	UN
S2	52	P (J1)	0.24	0.98	− 58.10	+ 10	49	III	PS
		T (J2)	0.64	1.00	− 25.52	+ 10	46	III	PS
S3	53	W (J1–J2)	0.80	0.93	− 59.42	+ 10	19	V	CN
S4	53	W (J1–J2)	0.43	0.32	− 59.66	+ 8	53	III	PS
S5	57	P (J1)	0.97	0.90	− 59.48	+ 10	15	V	CU
		W (J1–J3)	0.99	0.90	− 59.48	+ 10	14	V	CU
S6	54	W (J1–J2)	0.91	0.99	− 58.27	+ 8	10	V	CU
S7	45	T (J1)	0.41	1.00	− 25.65	+ 8	43	III	PS
S8	48	P (F)	0.91	0.98	− 58.10	+ 10	6	V	CU
		W (F–J1)	0.25	0.96	− 58.94	+ 10	39	IV	UN
S9	62	P (J1)	1.00	1.00	− 59.00	+ 10	16	V	CU
S10	62	W (J1–J3)	0.71	0.92	− 59.34	+ 10	33	IV	UN
S11	63	W (J1–J2)	0.97	0.96	− 59.05	+ 8	16	V	CU
S12	52	T (J2)	0.85	1.00	− 25.00	+ 8	39	IV	UN
S13	55	T (J2)	0.70	1.00	− 25.00	+ 10	47	III	PS
S14	43	P (J1)	0.18	0.93	− 59.17	+ 8	41	III	PS
S15	58	W (J1–J3)	0.57	0.96	− 59.09	+ 8	34	IV	UN
S16	58	W (J2–J3)	0.91	0.86	− 59.58	+ 10	21	IV	UN
S17	56	W (J1–J2)	0.33	0.90	− 51.14	+ 10	51	III	PS
S18	48	P (J1)	0.94	0.97	− 56.8	+ 10	6	V	CU
		W (J2–J4)	1.00	0.76	− 59.47	+ 10	13	V	CU
S19	47	P (J1)	0.54	0.90	− 59.42	+ 10	28	IV	UN
		W (J1–J3)	0.35	0.90	− 59.42	+ 10	38	IV	UN
S20	53	P (J3)	0.74	0.96	− 59.13	+ 10	26	IV	UN
S21	40	P (J3)	0.41	0.98	− 57.29	+ 10	27	IV	UN
		W (J1–J3)	0.21	0.86	− 59.47	+ 10	39	IV	UN
S22	36	P (J2)	0.77	0.85	− 59.40	+ 10	7	V	CU
		W (F–J2)	0.21	0.76	− 59.47	+ 10	36	IV	UN
S23	55	P (J1)	0.70	0.97	− 59.05	+ 10	16	V	CU
S24	48	P (J1)	0.89	0.91	− 59.27	+ 10	15	V	CU
S25	46	P (J2)	0.41	0.98	− 55.32	+ 8	32	IV	UN
		W (J1–J2)	0.27	0.96	− 59.00	+ 8	38	IV	UN
S26	50	W (J1–J2)	0.94	0.97	− 58.81	+ 10	7	V	CU
S27	54	P	0.77	0.95	− 59.32	+ 10	21	IV	UN
		W (J1–J3)	0.30	0.95	− 59.34	+ 10	47	III	PS
S28	46	W (J1–J3)	0.61	0.89	− 59.44	+ 10	24	IV	UN
S29	55	P (J1)	0.41	0.88	− 59.45	+ 8	47	III	PS
		W (J1–J2)	0.33	0.88	− 59.45	+ 8	51	III	PS
S30	57	P (J1)	0.97	0.98	− 58.10	+ 10	12	V	CU
S31	57	P (J1)	0.80	0.93	− 58.88	+ 10	23	IV	UN
		W (J1–J3)	0.74	0.92	− 59.05	+ 10	27	IV	UN
S32	57	P (J3)	0.48	0.93	− 59.40	+ 10	40	IV	UN
		W (J1–J2)	0.94	0.96	− 59.27	+ 10	14	V	CU
S33	46	W (J1–J2)	0.83	0.81	− 59.57	+ 8	14	V	CU
S34	54	W (J2–J3)	0.18	0.95	− 59.20	+ 8	51	III	PS
S35	41	T (J2)	0.85	1.00	− 25.58	+ 10	29	IV	UN
		W (J3–J4)	0.51	0.59	− 59.58	+ 10	33	IV	UN

P planar failure, *T* toppling failure, *W* wedge failure, *J* joint, *F* foliation, *CU* completely unstable, *UN* unstable, *PS* partially stable, F_1, F_2, F_3 are adjustment factors related to relative orientation of discontinuities and slope, F_4 adjustment factor for method of excavation

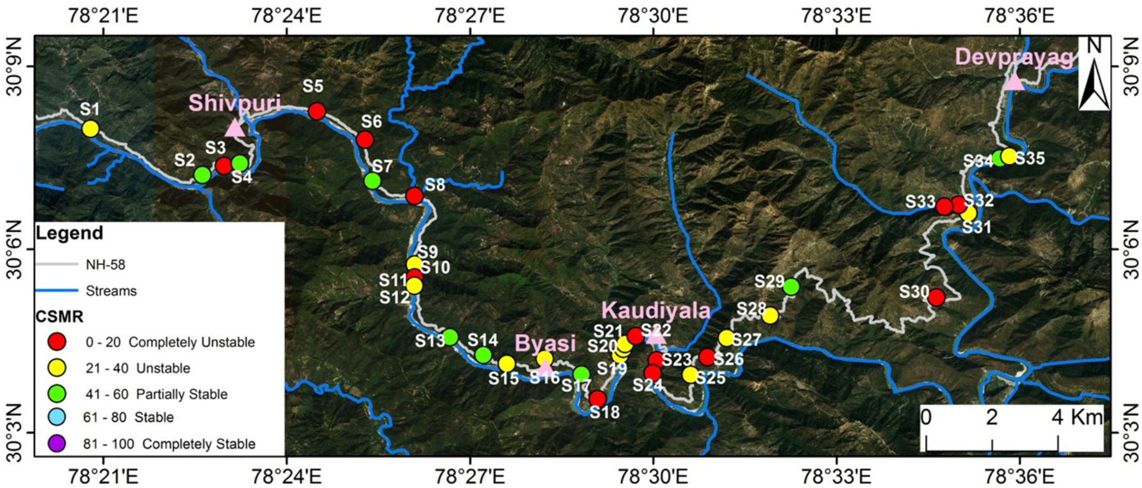

Fig. 5 Spatial distribution of CSMR stability classes along NH-58, Rishikesh–Devprayag

classes with an interval of 20 each. Spatial variation of RMR within the region shows that most of the sections along the stretch lie under poor category. However, maximum number of completely unstable to unstable slopes lies near Kaudiyala. Maps showing CSMR and SMR classes seem to be quite identical. However, few exceptions occurred at locations S3, S23 and S28. The SMR and CSMR of these slopes lie on boundary of adjacent class.

Structurally controlled failures are very prominent in the study area due to highly fragile conditions posed due to intensely jointed rock mass. The kinematic analysis of slope determines the possible mode of failures irrespective of its cause. The orientations of each slope face and the discontinuity set present within the rock mass were measured on outcrop during field survey. These recorded planes were plotted on Schmidt net to determine angular relationships among them which enabled to identify different failures (planar, toppling and wedge) that are likely to occur at discrete studied locations. The results obtained from kinematic analysis have been illustrated in Fig. 6. For instance in slope S19, the most probable mode of failure is of wedge type due to intersection of joint set J1 and J3 because the line formed by the intersection of these joint sets is plunging is plunging in same direction as slope and amount of plunge is greater than friction angle and smaller than slope inclination. However, joint set J1 have dip direction nearly parallel to slope and dip amount of joint is falling in between slope inclination and friction forming perfect conditions for planar mode of failure to occur. However, at location S13, joint set J2 is dipping opposite to slope with steep amount forming favourable conditions for toppling failure to occur. Similarly, all possible modes of failures at all locations have been mentioned in Table 6 along with the joint set responsible for failure.

Conclusions

Rock mass classification is an integral approach for slope stability assessment and vulnerability analysis. It is rapid and easy to apply at low cost which provides quick assessment of rock mass quality. It also provides appreciable confidence during preliminary slope stability assessment. Slope stability investigations along road cut slopes from Rishikesh to Devprayag had provided brief overview and better insight of slope instability problems in highly fragile conditions of Himalayan rock mass. Most part of investigated section is continuously experiencing huge tectonic stress leading to intense deformation, fragmentation and generating additional discontinuities which provoked large-scale slope instability in the Himalayan region. Intense deformation and inevitable climatic conditions along with some adverse anthropogenic causes are major triggering factors of slope instability in the region. Continuous out flow of groundwater at location S21 near town Kaudiyala is hampering stability to a great extent. Most of the critical slopes identified along the highway are located near Kaudiyala which comprises of sandstone and slate of Ramgarh and Tal formation. By SMR and CSMR, road cut slopes (S5, S6, S8, S9, S11, S18, S22, S23, S24, S26, S28, S30, S32 and S33) are falling under completely unstable stability grade and need immediate remedial measures. Such slopes should be reinforced by spot bolting, constructing ditches and installing nets to retain potential falling blocks. However, rock slopes having < 10 (S6, S18, S22, S26 and S30) should be re-excavated to attain better safety along highway. Many structurally controlled failures were quite evident from discrete locations and kinematic study revealed that most of the studied locations are under significant threat of planar, toppling and wedge modes of failures. Results obtained by kinematic analysis have been

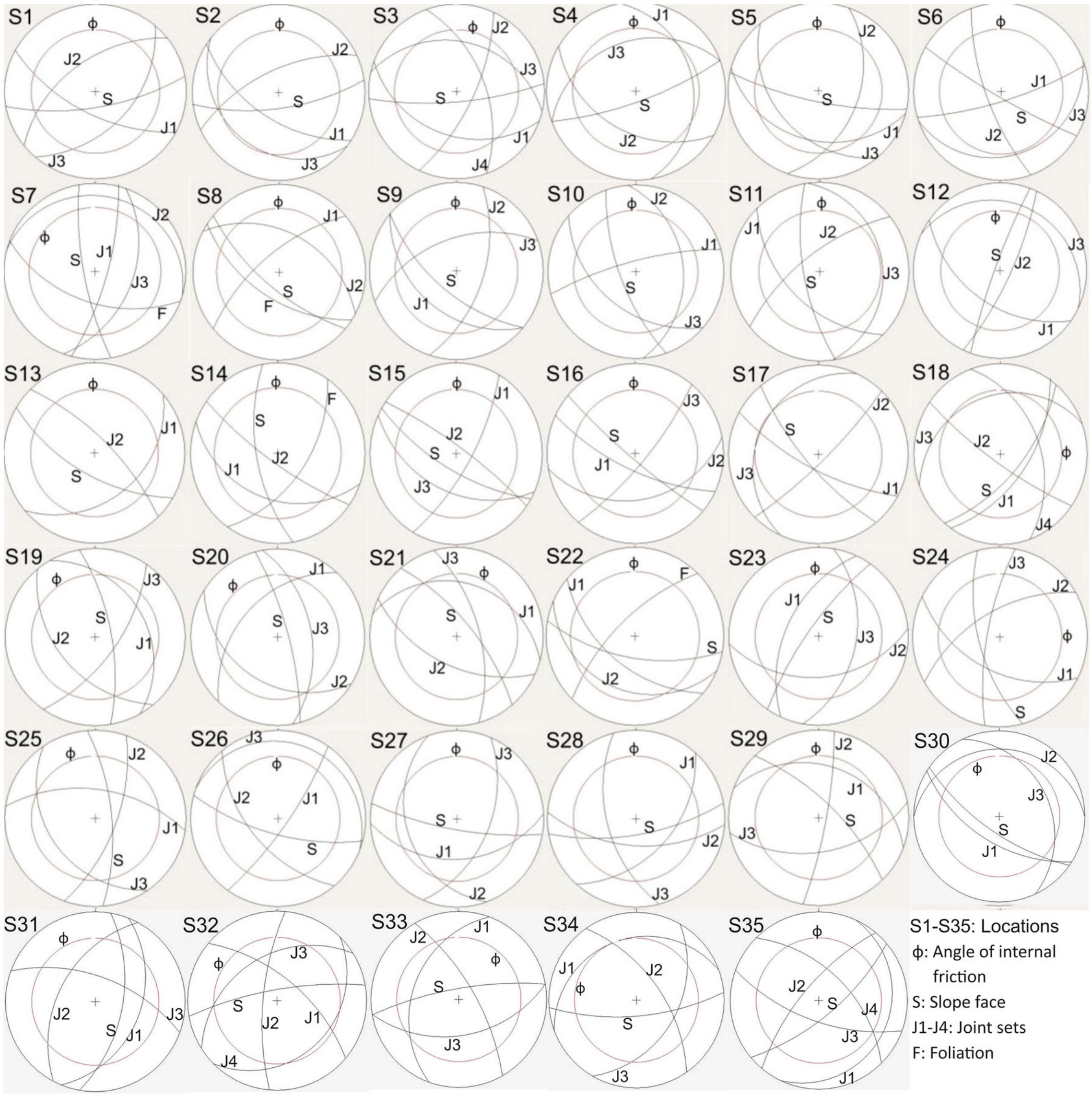

Fig. 6 Kinematic analysis of road cut slopes illustrating mutual geometrical relationship between slope face and discontinuities within the rock mass at discrete location in study area

corroborated with the results obtained by rock mass classification schemes. Different proxies employed to assess stability of cut slopes are quite identical to each other and also showing good agreement with the prevailing field conditions. The research output invokes such schematic assessment should be performed regularly to build much safer and economic design along highways in tectonically active regions like Himalayas. Proper planning and implementation of suggested geotechnical measures for slope stability along NH-58 can reduce possible hazards posed due to slope failures. Further more detailed investigations are required to reduce fatalities along the highway as major rockfall and mass failure events are common in the investigated region which causes huge destruction to life and property. The study will help in attaining stable road cut slopes and the suggestive remedial measures will improve the stability of slopes along the highway. The outcome of the study will give insights to proper planning and design of cut slopes in the hilly terrain.

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