Stability Assessment of Cut Slopes Along Shivpuri–Kaudiyala Road (NH-58), Uttarakhand Himalayas

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Abstract In the present study, slope stability assessment of selected cut slopes on a road stretch of approximately 25 km length along the National Highway (NH-58) between Shivpuri and Kaudiyala in the Lesser Himalaya of Uttarakhand has been carried out. This NH-58 connects Rishikesh with Badrinath and Kedarnath, two important Hindu shrines in Uttarakhand and also the border areas of the country. Hence, it is obvious that this highway is important from the pilgrimage, tourism and defense point of view. The present study includes characterization of rock mass, computation of slope mass classification ratings and comparison of different rock mass classification systems (such as RMR, GSI, SMR and CSMR) for 25 numbers of rock slopes along the selected road stretch. Also, kinematic analyses have been performed for all these slopes to understand the mode of slope failure. Further, stability analyses of a few significant road cut slopes have been carried out using a finite element tool.

Keywords Slope stability · Lesser Himalayas · Rock mass classifications · Kinematic analysis · Finite element method

1 Introduction

Road networks and highways play an indispensable role in the Garhwal Himalayan terrains for mass conveyance, tourism and its socioeconomic development. Along highways, stability of slopes is of major concern for ensuring a safe transportation solution. Slopes may fail by natural or anthropogenic agents that lead to disruption in traffic flow, loss of properties and lives and environmental degradation by soil erosion and loss of plantation. One of the common and often neglected areas of concern is

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the systematic geological and geotechnical investigation before excavation of a road cut. Unscientific design of a road cut may weaken toe of a natural slope, which may fail in rainy season even due to slightest of rainfall or in the wake of an earthquake event. Thus, slopes may become highly vulnerable and a threat to local commuters.

According to researchers (Dudeja et al. 2017; Siddique et al. 2017), landslides generally and recurrently occur in the Garhwal Himalayan terrains due to the presence of geologically weak rocks, high rainfall intensity during the monsoon season, tectonically induced seismicity and occasionally due to anthropogenic activities like blasting of tunnels for hydropower projects, unplanned excavation or sideway cuttings for road widening (Sati et al. 2011) and deforestation. In recent times, frequency of landslides in the Himalayan region has raised due to heightened infrastructure development activities like road widening and hydropower projects (Singh et al. 2010).

The present study endeavors to perform stability assessment of selected road cut slopes along Shivpuri (after Rishikesh)–Kaudiyala (before Devprayag) route of NH-58 in the Uttarakhand Himalayas. This is the busiest route in this region as every year a huge number of pilgrims access this route for traveling to the Char Dham shrines. This route is also having strategic importance as it connects to the international borders of the country. Another reason to choose this stretch as study area is that large-scale slope failures and associated problems are very common in this region. All of these need immediate stability evaluation and effective control measures to reduce the related vulnerabilities. For investigating the vulnerable slopes in this region, field survey has been carried out, and pertinent data required for different rock mass classification systems like RMR, GSI, SMR and CSMR have been collected. These data were then used to evaluate stability of the screened road cut slopes in this region. Kinematic analysis technique was also used to identify types of slope failures and failure direction. Two-dimensional stability analysis software based on finite element code was also employed to evaluate stability condition of two critical slopes. From all these analysis, it has been observed that nine slopes are stable, four slopes are having potential of wedge failure, and rests of the twelve slopes are susceptible to planar failure. These results indicate that the techniques employed in this study corroborate each other in assessing the slope stability which is a prerequisite for designing appropriate remedial measures to prevent slope failures and minimizing damage consequences. Overall, this study gives an insight into the landslide dynamics pertinent to slope failures in the lesser Himalayan region through kinematic and finite element analysis and presents a quantitative comparison between the available and popular slope mass classification methods.

2   Study Area

The present study area is a part of Garhwal Himalaya along the national highway NH-58 from Shivpuri to Kaudiyala in Tehri Garhwal district of Uttarakhand state. This area is located between latitude 30°4′9.9″ to 30°8′15.2″ and longitude 78°24′29.7″

Fig. 1 Stretch for all the
studied slopes along NH-58
(from Google map)
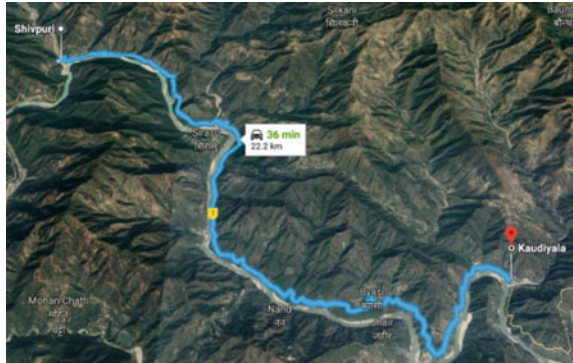
to 78°30′59″. The highway is situated along right bank of the Ganga River. This is an important route which connects Indo-Gangetic plain to hilly areas of Uttarakhand. This road stretch has been selected primarily because of the frequency and extent of damage which take place every year due to landslides. The road stretch on which the critical slopes were identified and studied is shown on a Google map in Fig. 1.

Geologically, the present study area falls under a part of Garhwal Lesser Himalaya which lies between the Greater Himalaya and Siwalik Range and bounded by Main Central Thrust (MCT) and Main Boundary Thrust (MBT), respectively (Heim and Gansser 1939). The Lesser Himalayan belt is one of the most structurally complex litho-tectonic units of Himalaya. The slopes investigated in this study include meta-sedimentary rock and meta-volcanic rock (Frank et al. 1995). During the field survey, the rock types encountered in the studied slopes are predominantly sandstone, but shale, limestone, slate and phyllite are also present to some extent.

The climatic conditions in the Lesser Himalaya are also very diverse and extreme in terms of amount of rainfall and fall in temperature during winter. The rainy season follows the monsoon cycles which begins in this region from June to August. The winter season is very cold particularly from December to March. Throughout the year, the temperature varies from -3 to 30 °C, and maximum rainfall is about 250 cm (Lawrence 1977).

3 Slope Stability Assessment from Rock Mass Classification Systems

In this study, the rock slopes were selected in such a way that they have varied geological and slope instability conditions. The data collected from field include details of the slope (its location, height and orientation), rock type, joint set numbers, joint spacing, joint condition (roughness, weathering, infilling), joint alteration, joint orientation, rock mass structure, hydrological condition and compressive strength evaluation from Schmidt hammer's rebound number.

Fig. 2 Field photographs of
some studied slopes

These field data were collected to determine GSI, RMR, SMR and CSMR of
the studied slopes. Also, slope profiles at two locations have been mapped from the
coordinates obtained by a laser distance meter instrument. This geometry of slopes is
a basic input to perform stability analysis by finite element method. Field photographs
of some of the studied slopes are shown in Fig. 2.

Once all the field data have been collected and compiled, different rock mass
and slope mass classification systems were used to evaluate stability of the studied
slopes. In the present study, the taken rock mass rating systems are: Rock Mass
Rating (RMR), Geological Strength Index (GSI), Slope Mass Rating (SMR) and
Continuous Slope Mass Rating (CSMR).

RMR is calculated according to Bieniawski's method (1989) by adding rating
values for five parameters: (i) strength of intact rock, (ii) rock quality designation
(RQD) value (measured or estimated), (iii) spacing of discontinuities, (iv) condi-
tion of discontinuities and (v) water inflow through discontinuities. According to
RMR$_{basic}$ system, five classes are defined as very poor rock (Class V: 0–20), poor
rock (Class IV: 20–40), fair rock (Class III: 40–60), good rock (Class II: 60–80) and
very good rock (80–100).

In this study, the parameters of discontinuities of the selected slopes have been
found to vary considerably. Joint spacing and opening also show a wide range of
values. The presence or absence of filling was noted along with type of filling those
discontinuities. RQD value was estimated from its empirical relationship with the
number of joints per cubic meter or volumetric joint count (Jv). The hydrological
conditions of the slopes were also observed. In most of the cases, the slopes were
found to be dry. Along with these data, attitude of discontinuities and slope angles

were also measured. For evaluating the compressive strength of rock mass (UCS), rebound numbers were taken from each studied slopes which showed large variation according to different rock type. UCS is calculated with the help of the following correlation from (Saptono et al. 2013):

$$UCS = 0.308R^{1.327} \qquad (1)$$

where R = Rebound hammer value from N-type hammer.

The GSI system is another rock mass classification technique proposed by Hoek and Brown (1997). This rock mass classification system which is an easy method for field application is primarily based on the blockiness of the rock mass and the surface conditions of discontinuities. Later, there have been many modifications of the GSI, and a quantitative method to estimate more precise values was given by Sonmez and Ulusay (2002) which provided a modified chart. This modified quantitative rock mass classification is based on the structure rating (SR) and surface condition rating (SCR). SR is based on volumetric joint count (Jv), while SCR depends on the roughness, weathering and infilling in joints. The values of Jv and SR are given in the chart to obtain the rating for SR. The modified chart represents five rock mass categories ranging between 5 and 100. The relevant correlations are as follows:

$$SR = -17.5 \ln(J_v) + 79.8 \qquad (2)$$

$$SCR = R_r + R_w + R_i \qquad (3)$$

To determine GSI, structure of rock mass and surface condition of the discontinuities has been studied in detail in the field. For surface condition rating, data on degree of rock mass weathering, roughness and infilling material were collected. Surface roughness data show a wide range from very rough to slickensides. Weathering was found to be varied from low to decompose state.

In Slope Mass Rating (SMR) approach (Romana 1985), stability of rock slope is evaluated from Bieniawski's Rock Mass Rating (RMR) (Bieniawski 1989) by adding adjustment factor of the joint-slope relationship and adding a factor depending on method of excavation (Romana et al. 2003).

$$SMR = RMR_{basic} + (F_1 \cdot F_2 \cdot F_3) + F_4 \qquad (4)$$

where RMR_{basic} is evaluated according to Bienaiwski (1989, 1979) by adding the rating of five parameters. Here, F_1, F_2, and F_3 are adjustment factors related to joint orientation with respect to slope orientation, and F_4 is the correction factor for method of excavation.

One of the recent popular techniques, Continuous Slope Mass Rating (CSMR) is also utilized in this study for slope stability assessment of rock slopes. This rating system was proposed by Tomas et al. (2007) in order to get more precise evaluation

of stability grades. It has been noticed that SMR value slightly deviates from real-field condition. This may occur during computation of adjustment factors when the exact value lies at border of predefined class interval (Umrao et al. 2011). However, consideration of continuous functions in CSMR has suppressed this problem and made this method a robust technique while dealing with assessment of slope stability.

To compute CSMR, the adjustment factors ratings (F_1, F_2 and F_3) were modified, while other parameters and method are similar to SMR. The modified adjustment factors are defined as

$$F_1 = \frac{16}{25} - \frac{3}{500} \arctan\left\{\frac{1}{10}|A| - 17\right\} \tag{5}$$

where A is $|\alpha_j - \alpha_s|$ is for planar failure, $|\alpha_j - \alpha_{s^-} - 1|$ for toppling failure and $|\alpha_i-\alpha_s|$ for wedge failure.

$$F_2 = \frac{9}{16} - \frac{1}{195} \arctan\left\{\frac{17}{100}B - 5\right\} \tag{6}$$

where B is β_j for planar failure, β_i for wedge failure, while F_2 remains 1 for toppling mode of failure.

$$F_3 = -30 + \frac{1}{3} \arctan C \tag{7}$$

where C is $(\beta_j - \beta_s)$ for planar failure, and $(\beta_j - \beta)$ for wedge failure. Also,

$$F_4 = -13 - \frac{1}{7} \arctan(C - 120) \tag{8}$$

where C is $(\beta_j - \beta_s)$ for toppling failure.

In all these above equations, α_s is the dip direction of slope, α_j is the dip direction of joint, β_s is the dip amount of slope, β_j is the dip amount of joint, α_i is the dip direction of line formed by the intersection of two discontinuity, and β_i is the amount of plunge of line formed by the intersection of two discontinuity. The value of arctan is in degrees.

The stability classes of SMR values, rock mass description, stability and probability of failure given by Romana (1985) are also applicable for CSMR classification Table 1.

In the present study, SMR and CSMR values were calculated from several rock mass and slope mass parameters based on visual inspection and laboratory experimentation. The result illustrates that 1 slope is stable, 7 slopes are partially stable, 8 slopes are unstable, and 9 slopes fall under completely unstable condition. The results of RMR, SMR and CSMR and their inferred stability grade are shown in Table 2. The stable, partially stable, unstable and completely stable slopes as evaluated from the rock mass classification systems have been shown in Fig. 3 with their respective locations on a Google map excerpt.

Table 1 Various stability classes as per SMR values (Romana 1985)

Class No.	V	IV	III	II	I
SMR value	0–20	21–40	41–60	61–80	81–100
Rock mass	Very bad	Bad	Normal	Good	Very good
Stability	Completely unstable	Unstable	Partially stable	Stable	Completely stable
Failure	Big planar or soil-like or circular	Planar or big wedge failure	Planar along some joint and many wedge failure	Some block failure	None
Probability of failure	0.9	0.6	0.4	0.2	0

From the present study, it has been observed that SMR values obtained for different slopes slightly deviate from computed CSMR values. This difference in values is due to the consideration of discrete and continuous functions in SMR and CSMR, respectively. Hence, it may be apprehended that the CSMR values are much closer to real prevailing field conditions.

The GSI values for the 25 slopes obtained in the present study were compared with the RMR values. It has been already established that RMR can be predicted from GSI and the relation between GSI and RMR_{89} after (Hoek and Brown 1997) is as follows (Singh and Goel 1999):

$$GSI = RMR_{89} - 5 \ (\text{for } GSI > 18) \tag{9}$$

While studying a few road cut slopes in Garhwal Himalaya (Sarkar et al. 2012; Sarkar et al. 2012) also found:

$$GSI = RMR_{89} - 9 \tag{10}$$

For this study, the GSI and RMR values have been plotted, and a new correlation has been established (Fig. 4):

$$GSI = RMR - 6 \tag{11}$$

Further, SMR and CSMR values have been also plotted in Fig. 5, and a correlation has been found:

$$CSMR = 0.8 \ SMR + 3.8 \tag{12}$$

Table 2 Comparison of RMR$_{basic}$, SMR and CSMR values for the studied slopes along with their stability grades (SG)

Slope	RMR$_{basic}$	SMR	SG	CSMR	SG
1	64	24	US	19	CUS
2	64	56	PS	47	PS
3	55	47.5	PS	49	PS
4	53	13	CUS	24	US
5	38	13	CUS	2	CUS
6	59	9	CUS	38	US
7	54	64	S	64	S
8	45	20	US	17.4	CUS
9	63	65.5	S	55	PS
10	51	44.2	PS	43	PS
11	55	23	US	19	CUS
12	53	13	CUS	16	CUS
13	62	47	PS	47	PS
14	62	54	PS	46	PS
15	48	15.5	CUS	7	CUS
16	45	4	CUS	7	CUS
17	48	39	US	30	US
18	43	15.3	CUS	7.5	CUS
19	38	4	CUS	4	CUS
20	58	18	CUS	22.6	US
21	62	37	US	24	US
22	64	31	US	23.5	US
23	60	26	US	30	US
24	30	18	CUS	21	US
25	58	58	PS	52	PS

Here, *US* unstable, *CUS* completely unstable, *PS* partially stable and *S* stable

4 Kinematic Analysis of Slopes

Kinematic analysis has been performed to understand mode of slope failure. Kinematic analysis evaluates the potential failure mechanisms (e.g., planar, wedge or toppling failures) by analyzing the discontinuity-slope relation. Discontinuities considered in the study are primarily bedding, foliation and joint planes. A plane failure is likely to occur when a discontinuity dips in the same direction (within 20°) as the slope face, at an angle gentler than the slope angle but greater than the friction angle along the failure plane. A wedge failure may occur when the intersection line of two discontinuities forming the wedge-shaped block plunges in the same direction
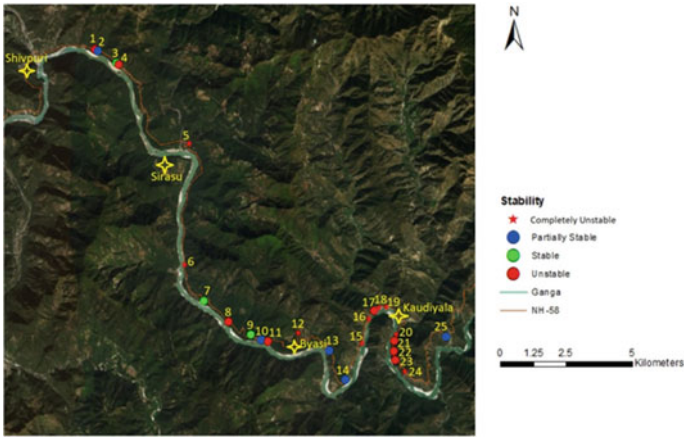
Fig. 3 Locations and evaluated stability of studied slopes along NH-58
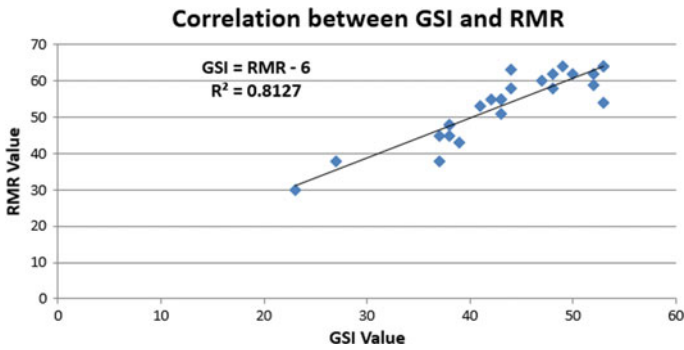

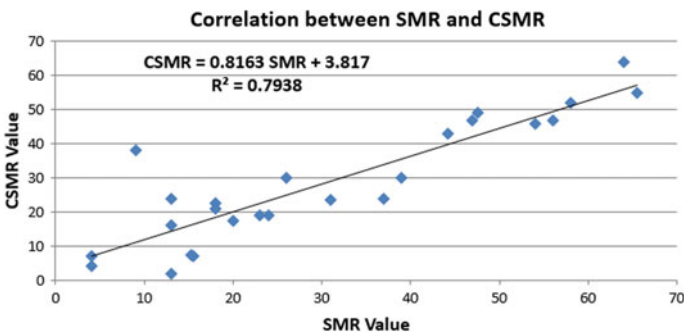**Fig. 4** Correlation between computed GSI and RMR values for the studied slopes

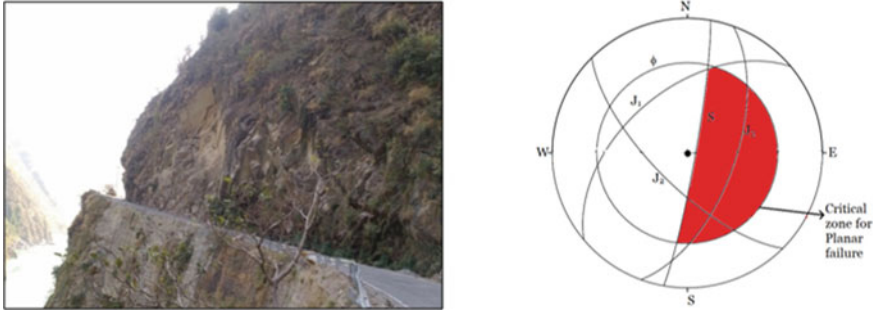**Fig. 5** Correlation between computed SMR and CSMR values for the studied slopes

Fig. 6 Kinematic analysis of slope S-16 with site photograph and stereo-plot

as the slope face and the plunge angle are less than the slope angle but greater than the friction angle along the planes of failure (Hoek and Bray 1981). Out of all 25 slopes studied in this work, four slopes (S-4, S-9, S-21, S-25) are predicted to undergo wedge failure by typical double plane sliding and occasional small planar failure, whereas twelve slopes (S-1, S-5, S-6, S-8, S-11, S-12, S-15, S-16, S-17, S-18, S-19 and S-20) are predicted to undergo planar failure. The rest of the slopes are found to be stable due to favorable discontinuity orientations and high shear strength. A typical kinematic analysis of slope S-16 with site photograph and stereo-plot has been shown in Fig. 6.

5   Finite Element Analysis of Slopes

It has been observed that numerical modeling is a unique approach for slope stability analysis as it encompasses slope geometry, layering of strata, different material properties (elastic and plastic state) and different constitutive models which result into a reliable quantitative term, factor of safety of the slope. For determining factor of safety of slopes, in this study, a FEM program RS2 9.0 has been utilized by incorporating engineering and physical properties of slope material determined in laboratory and field. The code, RS2 9.0, is a 2D finite element program for slope stability analysis in which finite element slope stability analysis can be done using the shear strength reduction (SSR) method. It also provides user defined Mohr–Coulomb or Hoek–Brown strength parameters.

In this study, slope stability analysis of two selected critical slopes (S-2 and S-4) has been carried out. By definition, the factor of safety (FoS) of a slope is the "ratio of actual soil shear strength to the minimum shear strength required to prevent failure" or the factor by which soil shear strength must be reduced to bring a slope to the verge of failure (Duncan 1999). In the SSR finite element technique, elasto-plastic strength is assumed for slope materials. The shear strength values of slope materials are progressively reduced until the collapse occurs.
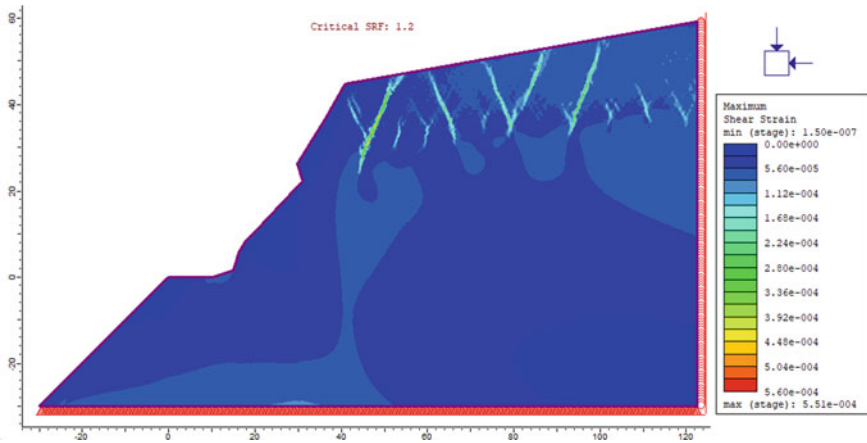
Fig. 7 Contour of the maximum shear strain for S-2

For Mohr–Coulomb material, shear strength reduced by a factor (of safety) F which can be determined from the equation:

$$\frac{T}{F} = \frac{C'}{F} + \frac{\tan \varphi}{F} \tag{13}$$

This equation can be rewritten as

$$\frac{T}{F} = C^* + \tan \varphi^* \tag{14}$$

In this case,

$$C^* = \frac{C'}{F} \text{ and } \varphi^* = \arctan\left(\frac{\tan \varphi'}{F}\right) \tag{15}$$

In this present study, factor of safety values for the chosen slopes have been calculated by using the generalized Hoek–Brown (GHB) criterion (Hoek et al. 2002). The obtained FoS values show that one slope is partially stable (FoS = 1.2) and another one is unstable (FoS = 0.49). The interpretation of results for both the slopes is shown in Figs. 7 and 8.

6 Conclusions and Recommendations

In the present study, 25 rock slopes (S-1 to S-25) along the stretch from Shivpuri to Kaudiyala in Uttarakhand Himalaya were selected for slope stability assessment. For all these slopes, the values or ratings of GSI, RMR$_{basic}$, SMR and CSMR were
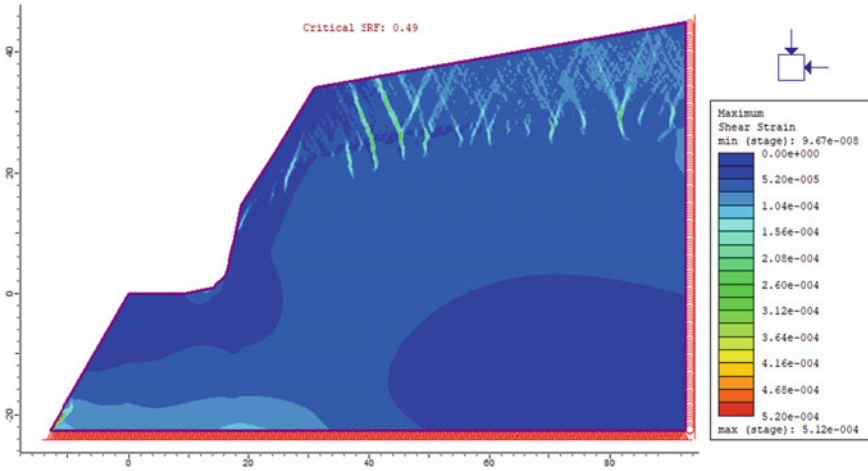
Fig. 8 Contour of the maximum shear strain for S-4

evaluated, and kinematic analysis was carried out. From these analyses, unstable slopes have been identified. These slopes need immediate remedial measures such as reinforcement by rock bolts and anchors as they are rock slopes and have layers of weak weathered rocks on top of hard rock stratum. Based on the kinematic analysis, it has been concluded that out of all 25 locations, four slopes are predicted to undergo wedge failure and occasional small planar failure, whereas the fifteen slopes are predicted to undergo planar failure. A table was constructed showing comparative values of all the ratings obtained from different rock mass classification systems. Further, correlations between GSI and RMR and SMR and CSMR have been established from the compiled pool of field data. However, this kind of correlation study needs more data to establish strong relationships with more confidence level. Also, stability analysis of two slopes has been performed by finite element analysis, the results from which substantiate the findings about the stability grade of those slopes by rock mass classification systems Table 2.

The present study will help in understanding the slope stability of the road cut slopes. The study shows the importance of such investigation before constructing the hill roads. Such study is also important to design adequate remedial measures which can improve the stability of slopes. The results of this study give deeper insights to landslide dynamics by a unique culmination of different slope mass classification systems, kinematic analysis and finite element analysis. The results from this study indicate that all the techniques corroborate with each other in assessing the slope stability if field and laboratory data have been critically obtained and analyzed. Finally, the results obtained here in this study will help in proper planning and design of road cut slopes in the hilly terrain, especially in the ongoing Char Dham Yatra project in Uttarakhand Himalayas.

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