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Geo-Mechanical Analysis of Landslide-Prone Road Cut Slopes along the National Highway-5, Powari to Akpa, Kinnaur District, Himachal Pradesh, North-Western Himalaya, India

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Abstract

Landslides are one of the most damaging geological hazards in the hilly and mountainous regions of India, including IHR (Indian Himalayan Region). Most of the National or State highways in the hills are affected by landslides of various magnitudes, attributing part from natural and triggering causal factors, as well as anthropogenic reasons like unplanned excavations. The National Highway-5, which connects the rest of the country with border areas of the region, also passes through important townships including the capital city of Shimla and district Headquarters of Solan, Shimla, Rampur and Kinnaur, thereby serving the both security as well as socio-economic purposes. Though the NH-5 gets impacted from landslides, particularly during monsoon, starting from Kalka to Kaurik border area, this research mainly focuses on the slope stability evaluation on the National Highway-5 and the adjoining slopes from Powari to Akpa using Rock Mass Rating (RMR), Slope Mass Rating (SMR), and Kinematics analysis. Seven road-cut slopes were identified for a detailed study to identify the causes and types of failure. The study reveals that the slopes, which are composed of good to fair categories of rock masses, fall under the completely unstable to partially stable conditions. Out of the seven slopes, two were critically unstable, whereas four were classified as unstable and one was partially unstable with localized zones exhibiting potential instability; however, three were classified as planar, another three as wedge, and one slope exhibits compound involving both the planar and wedge conditions.

Keywords

Landslide, RMR, SMR, Kinematic Analysis, Wedge and Planar Failure

1. Introduction

Slope failures in the mountainous region are caused by tectonic settings and other geological processes such as erosion, weathering, and denudation, which are exacerbated by human interactions [1]-[3]. Through repeated road excavations with a lack of proper knowledge about the geological conditions and rock mass characteristics, the likelihood of slope failure has increased manyfold in mountainous regions that are dynamically active [4]-[8]. The construction of roads, hydroelectric, and other infrastructure projects in the Himalayan region has triggered landslides in numerous ways by altering the route of water and steepening the slopes [9] [10]. Himachal Pradesh is mainly a hilly region with climate conditions and a rugged landscape [11] [12]. In dynamically active areas like Himachal Pradesh, the potential for slope failure increases day by day [3]-[6] [13] [14]. This is a challenging problem in the mountainous terrain, inflicting both ecological damage and the loss of lives [15] [16]. Globally, mass movement events have caused economic damages of a whopping 8 billion US dollars and have also directly or indirectly affected around 4.8 million people worldwide in the years 1998-2017 [17]. India tops the charts in the world in deaths caused by landslides, with a scary number of around 11,000 deaths in the 12 years 2004-2016 [18]. Therefore, analysis of slopes before, during and post-construction of any infrastructure is necessary for evaluating the stability of slopes. SMR is a widely recognized geomechanical classification [19] [20] for categorizing slope failure parameters using the Rock Mass Rating. The rock mass rating, however, depends on field studies or assessment of rock samples in the laboratory that have been collected from the field, and some other parameters analysed in the field like rock strength, discontinuity spacing, rock quality discontinuity condition, and condition of groundwater. After the assessment of all these parameters, they are used to calculate rating [19] [20]. The present research is focused on geological and mechanical aspects to analyse the conditions of road-cut slopes between Powari and Akpa, Himachal Pradesh, on the NH-5. The road-cut slopes in the study area are steep and highly jointed, so the kinematic analysis technique is employed to determine the type of failure in the area.

2. Study Area

The research area, between latitudes 31˚32'84'', 31˚34'58'', and longitudes 78˚16'47'', 78˚23'35'', belongs to Kinnaur district of Himachal Pradesh, India, and includes a part of National Highway-5 that extends for about 35 km from Powari to Akpa and shares a boundary with the neighbouring country, China. The whole stretch of the highway in the study area is exposed to rugged topography, near stable and unstable rock masses, steep slopes, deformed rocks, structural features, and many other geological features like small folds, drainage systems by some waterfalls, small river tributaries, etc. The deformed rock slopes left exposed pose a very high risk to the commuters, the national highway and its infrastructure. The frequent blockades of highways due to landslides, ranging from an hour to a few hours and even days, cause hardship for the travelling public as well as the inhabitants, thereby causing socio-economic, environmental and strategic challenges (**Figure 1**). Indicates the study area as well as the location of the rock slope sample collected from the field.

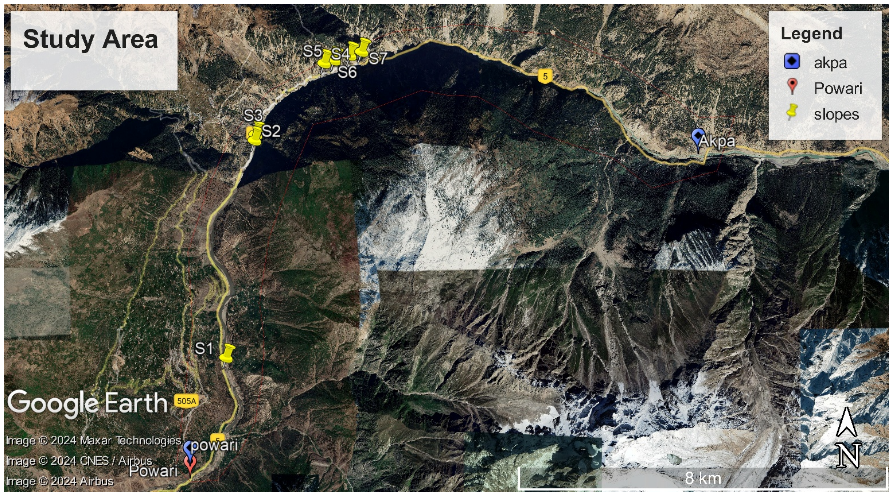

Figure 1. Location of rock slopes along NH-5, Powari to Akpa (Google Earth Image).

3. Geological Setting of the Study Area

As indicated in (**Figure 2**) the research area lies in the Vaikrita Group, which is part of the Higher Himalayan Crystalline (HHC). This group is underlain and overlain by the Jutogh and Haimanta groups, respectively [11] [21] [22]. The Higher Himalayan Crystalline (HHC) is the basement layer for the Phanerozoic Tethyan Sedimentary Deposits [23]-[25].

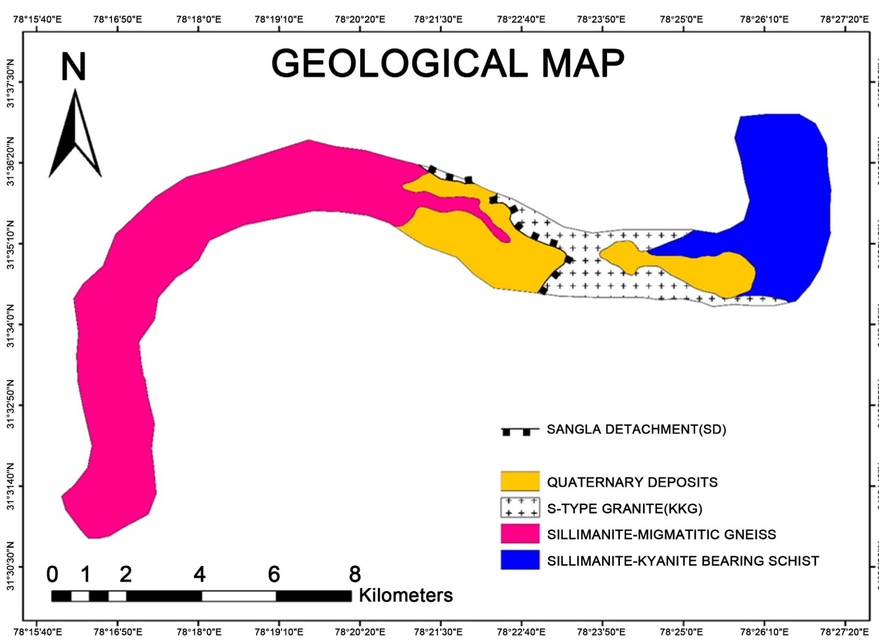

Figure 2. Geological map of the study area.

It mainly consists of Paleoproterozoic to early Palaeozoic metasediments (psammitic and pelitic) and highly viscous and silica-rich migmatitic rocks, which are altered protoliths of the Neogene leucogranites [11] developed during the collision events of the Himalaya Mountains [11] [26] [27]. The Tethyan sequence and higher Himalayan crystalline are divided by the Sangla Detachment fault [28]-[30]. The Vaikrita Group of the Kinnaur area has been divided into three formations: Kharo, Morang, and Shiasu [24]. The Kharo Formation is tectonically related to the Rohtang Gneissic Complex [31] and the Kulti Formation [32] of the Manali and Lahaul areas. The Vaikrita Group extends across the Karcham Group along the Vaikrita Thrust and consists of varieties of gneissic rocks, such as granitic gneiss, banded gneiss, coarse-grained psammitic gneiss, psammitic gneiss with layering of quartzite rocks, and quartz-mica gneiss [25] [31]. The Vaikrita Group consists of a variety of rocks of the Neoproterozoic age [25] [33], like granite-gneiss, biotite-gneiss, and migmatitic gneiss-embedded metasedimentary rocks and Early Palaeozoic sedimentary rocks [25] [34].

4. Methodology

As described above, the study area is mainly composed of rock slopes with very thin soil cover and, therefore, assessed based on the geomechanical classification system, which includes RMR and SMR.

4.1. Rock Mass Classification

RMR is a technique for determining the quality and characteristics of a rock mass, also known as rock mass classification or rock mass rating system [35]-[37]. In the RMR system, six parameters were identified by Bieniawski [35], but after modification [36], five parameters were used to calculate the rock mass rating. The five parameters are UCS, RQD, spacing of discontinuity, joint condition, and groundwater condition. The current study determines the RMR_{basic} by using these five parameters. RQD is calculated with the help of the volumetric joint count (J_V) present in a unit length for all discontinuities [35]. It follows the mathematical equation given below

$$\mathrm{RQD} = 115 - 3.3\ \mathrm{J_V}$$

The spacing of a discontinuity depends on the average distance between two adjoining discontinuities. The joint conditions depend on several geological factors, such as weathering, erosion, discontinuity separation, infilling materials, persistence, and aperture. The groundwater conditions are based on the flow of groundwater, which is completely dry, wet, dipping, or flowing. The rating of all five parameters is given according to [36]. Finally, all the examined slopes are categorised based on their RMR_{basic} values.

4.2. Kinematic Analysis

Kinematic analysis is used to determine unstable slopes. It is the most commonly used technique for evaluating different types of slope failure. The stereographic projection method is used in this study, in which the observed values of the dip amount of discontinuity or strike direction of joint sets are plotted onto the Stereonet, and the type of slope failure is investigated in terms of slope orientation and internal friction angle of discontinuity. The stereoplot shows the mode of failure of the studied slopes [38] [39]. The angle of friction indicates the ability of rock mass to sustain shear stress and is determined with the help of forces that occur within the rocks that oppose any displacement marked between rock particles. Planar failure occurs when the strike direction of the discontinuity is within the 20-degree range, as the slope and dip angle of the planar discontinuity is smaller than the dipping angle of the slope face but greater than the friction angle. For wedge failure, the line of intersection must dip in the same direction as the slope face, while the intersection of the plunge line must be less than the slope face's dip but greater than the friction angle. The kinematics analysis depends on the Markland test and is dependent on the joints that occur in the rock mass as well as slope orientations [38] [40]. This geometric analysis during the field survey provided extensive awareness of all the possible structurally driven failures and indicated probable modes of failure at specific locations in the research areas. The stereoplot determines the joint plane along which the maximum probability of failure occurs. After demonstrating the mode of failure, SMR is computed for the joint plane along which the maximum chances of failure exist.

4.3. SMR (Slope Mass Rating)

Romana (1985) [19] adopted the SMR to evaluate the strength of rock slopes, which is based on the use of the RMR_{basic} or joint orientations (**Table 1**), which are then followed by the mathematical calculation presented below:

$$\mathrm{SMR} = \mathrm{RMR}_{\mathrm{basic}} + (\mathrm{F1} \cdot \mathrm{F2} \cdot \mathrm{F3}) + \mathrm{F4}$$

Where F1 is determined considering the parallelism between the dip direction of the joints and the slope of the face [19]. F2 is determined by the dip of joints in the case of planar failure and the plunge of the intersection of joints in wedge failure [19]. F3 is determined by the difference between the joint's dip amount and the slope face's dip amount in planar failure, the difference between the intersection of two joints (the plunge of the intersection and slopes) in wedge failure, and the sum of the values of the joint's dip angle and the slope face's dip angle in toppling failure. F4 can be calculated using the method of excavation [19].

F4—Excavation method:

Natural slope = +15, blasting or mechanical = 0, Presplitting = +10, deficient blasting = −8, Smooth blasting = +8, blasting = +8

The overall SMR value for various modes of failure defines SMR class, detail descriptions, stability ratings, failures, or required support. To develop efficient slope restoration procedures, extensive fieldwork and a strong engineering sense are required.

Table 1. Values of the Adjustment factors (after Romana, 1985) [19].

Types of failure	Adjustment Factors	Values and ratings				
P	$\lvert\alpha_j - \alpha_s\rvert$	>30˚	30˚ - 20˚	20˚ - 10˚	10˚ - 5˚	<5˚
W	$\lvert\alpha_i - \alpha_s\rvert$					
P/W	F1	0.15	0.4	0.7	0.85	1
P/W	$\beta_j - \beta_s$	<20˚	20˚ - 30˚	30˚ - 35˚	35˚ - 45˚	>45˚
P/W	F2	0.15	0.4	0.7	0.85	1
P	$\beta_j - \beta_s$	>10˚	10˚ - 0˚	0˚	0 (−10˚)	<(−10˚)
W	$\beta_i - \beta_s$					
P/W	F3	0	−6	−25	−50	−60

where: *P*—Planer failure *W*—Wedge failure; α_j—joint direction, α_s—Slope direction, α_i—Plunge of intersection, β_s—Slope dip, β_j—Joint dip.

5. Result and Discussion

Based on the detailed field observations of the study area, seven slopes were chosen to indicate the most common slope-instability situations observed along the analyzed highway corridor. Selection was based on slope geometry, lithology, degree of weathering, discontinuity features, indications of past instability, and probable influence on the highway. The geographical location and/or highway chainage of each slope were validated during the field studies. Even though the selected slopes do not include every slope throughout the corridor, they were chosen to reflect the primary geological, structural, and geomorphological factors associated with slope instability. A total of seven critical highway slopes that have been troubling the highway were identified for further investigation and analysis. The majority of the highway slopes were found fractured and jointed, dry and mostly barren, as indicated in the field photographs of the studied slopes in **Figure 3**. The stability assessments of the selected slopes were done using the RMR, SMR, and kinematics analysis. The RMR is calculated by adding the five given parameters [36] shown in **Table 2**. The compressive strength of the rocks is determined using field estimates [41], which comes in the low range, *i.e.*, 7 to 12. RQD is determined using the (J_V) volumetric counting number of joints per cubic meter in the joint set using the formula suggested by [42]; the ratings for RQD obtained range from 8 to 13. Similarly, all other parameters like discontinuity spacing, joint condition, and groundwater conditions have been studied in the field, and calculated values are shown in **Table 2**. Adding all these five parameters. RMR_{basic} has been calculated for each of the seven slopes (**Table 2**). Adding all these five parameters. RMR_{basic} has been calculated for each of the seven slopes (**Table 2**). By applying [36] classification, RMR_{basic} values of 46, 59, 54, and 54 at the landslide locations S1, S2, S4, and S5, respectively, can be classified as fair rock. Similarly, RMR_{basic} values of 64, 68, and 64 at locations S3, S6, and S7, respectively, are classified as good rock. On steeper slopes, the bedding plane can be daylighted from a wider range of angles throughout the slope face, leading to a higher failure rate than gentler slopes [43]. The slopes are generally steep to very steep (40˚ - 85˚) throughout the study area, which, coupled with other favourable parameters, increases the likelihood of slope failure. The three joint sets (J0, J1, and J2) are mainly observed throughout the research area. Table 3 shows the orientation of discontinuity and slope orientation data as well as substantially varied joint conditions of the selected slopes. The kinematic analysis performed on the selected slopes has helped to establish the mode of slope failure along NH-5 between Powari and Akpa, which was one of the prime aims of the study. Rock excavation for analysing the joints and discontinuity structures, whereas exposed outcrops from the road cuts selected to evaluate variation in the rock mass or mechanical and geological structure of the outcrops.

Kinematic analysis is carried out based on discontinuities, slope face, bedding plane, and angle of internal friction [36]. Friction angle of 30˚ was taken to fulfill both frictional conditions and kinematic conditions for the different failure types. The potential mechanisms of failure of seven selected rock cut slopes were also evaluated by kinematic analysis using Stereonet version 11.4.3. For each slope, a

Table 2. Evaluation of Rock mass ratings at different locations in the field study.

SLOPE No	UCS	RQD	JS	JC	GWC	RMR (BASIC)	CLASS	CLASS TYPE	STABILITY	ROCK TYPE
S1	7	8	8	8	15	46	III	FAIR	PU	GNEISS
S2	12	8	10	14	15	59	III	FAIR	PU	GNEISS
S3	12	13	10	14	15	64	II	GOOD	S	GNEISS
S4	12	11	8	8	15	54	III	FAIR	PU	GNEISS
S5	12	8	15	14	15	54	III	FAIR	PU	GNEISS
S6	12	13	15	13	15	68	II	GOOD	S	GRANITE GNEISS
S7	12	8	10	19	15	64	II	GOOD	S	GRANITE GNEISS

Table 3. Slope Mass Rating using adjustment factors based on field study.

SLOPE NUMBER	RMR (basic)	$\lvert\alpha_j - \alpha_s\rvert$ or $\lvert\alpha_i - \alpha_s\rvert$	β_j or β_i	$\beta_j - \beta_s$ or $\beta_i - \beta_s$	F1	F2	F3	F4	SMR	SMR CLASS	STABILITY CLASS
S1	46	−7	60	−2	1	1	−60	0	14	V	CU
S2	59	−12	35	−15	1	0.7	−60	0	17	V	CU
S3	64	20	36	−9	0.7	0.85	−60	0	28.3	IV	U
S4	54	25	36	−24	0.4	0.85	−60	0	33.6	IV	U
S5	54	42	40	−28	0.15	0.85	−60	0	46.35	III	PS
S6	68	21	54	−26	0.7	1	−60	0	26	IV	U
S7	64	15	38	−11	0.7	0.85	−60	0	28.3	IV	U

Figure 3. Field photograph of studied slopes: (a) S-1 jointed rock mass of gneiss. (b) S-2 jointed gneiss rock mass type. (c) S-3 planar failure in gneiss rock type. (d) S-4 wedge failure in jointed gneiss rock mass type. (e) S-5 wedge failure in gneiss rock mass. (f) S-6 shows wedge failure in granite-gneiss rock mass type. (g) S-7 planar and wedge failure in granite-gneiss rock mass.

stereograph was generated to provide joint input variables, including internal friction angle, slope (SL), bedding joint (J0), and joint (J1 and J2) orientations (**Figure 4**). The kinematic study indicated mainly planar, wedge, and compound failures involving both planar-wedge modes of failure. However, the analysis of stereo plots indicates that the maximum potential for planar and wedge failures occurs along the bedding plane (J0) and joint plane (J2). RMR and SMR values indicated in **Figure 5** display the trends of RMR values with their corresponding SMR values. This demonstrates that even with high-quality rock mass, the stability of rock slopes can be compromised by unfavourable joint orientations, making them susceptible to slope failure. It highlights the critical role that joint orientation plays in determining slope stability. According to SMR ratings, the findings

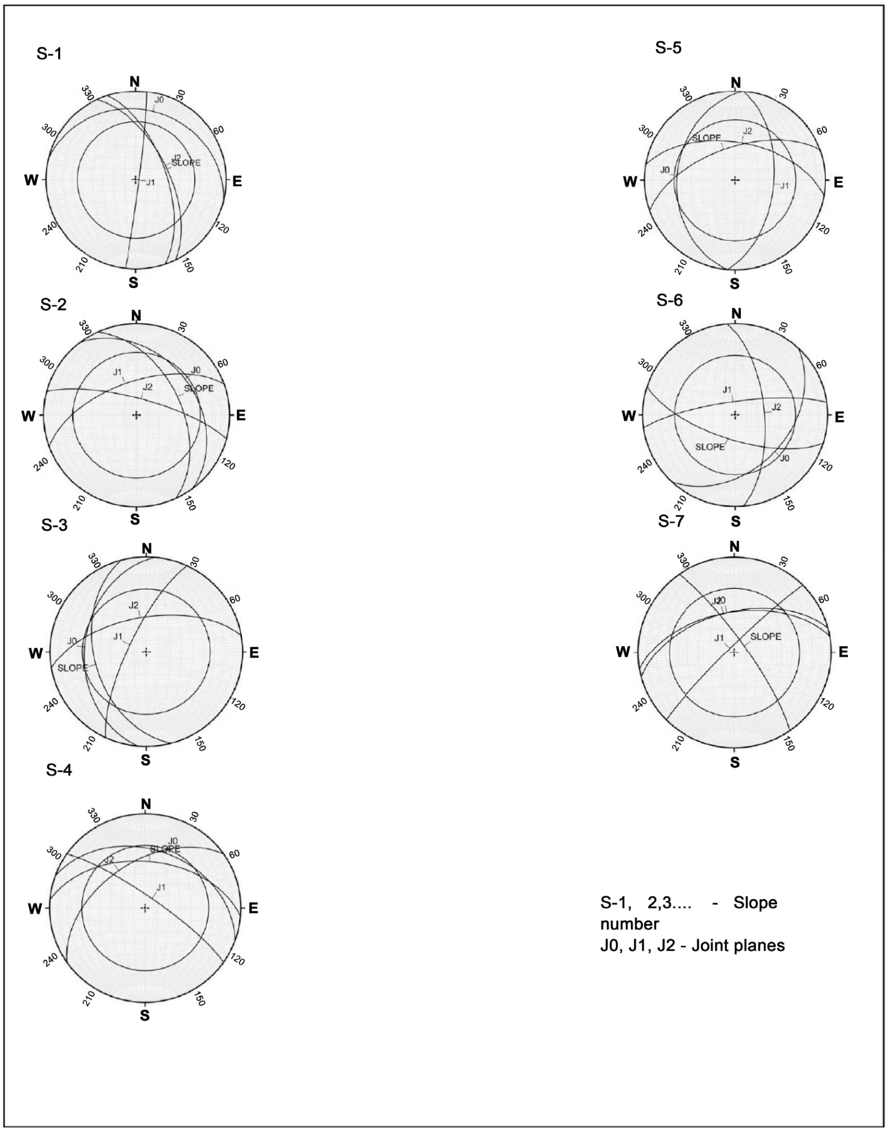

Figure 4. Stereoplots and associated mode of failure for studied slopes (S1 to S7), respectively.

demonstrate that the stability of different slopes ranged from partially stable (Class III) to completely unstable (Class V) at the selected locations. Depending on the modes of failure, each slope has been given a score. Slopes S-1 and S-2 were found to be completely unstable for planar failure along joint J0, and slope S-3 was found to be unstable for planar failure along joint J0. In terms of wedge failure, the SMR rating shows that S-4, S-5, and S-6 were found to be partially stable and unstable, while S-7 was determined to be unstable for both planar and wedge failure along joint J0&J1. The kinematic analysis was understood as a geometrical screening tool for discovering failure modes that are kinematically possible under the reported static slope and discontinuity orientations. Therefore, the findings reflect the potential for planar and wedge failures, rather than the probability of failure. No probability analysis was undertaken due to the

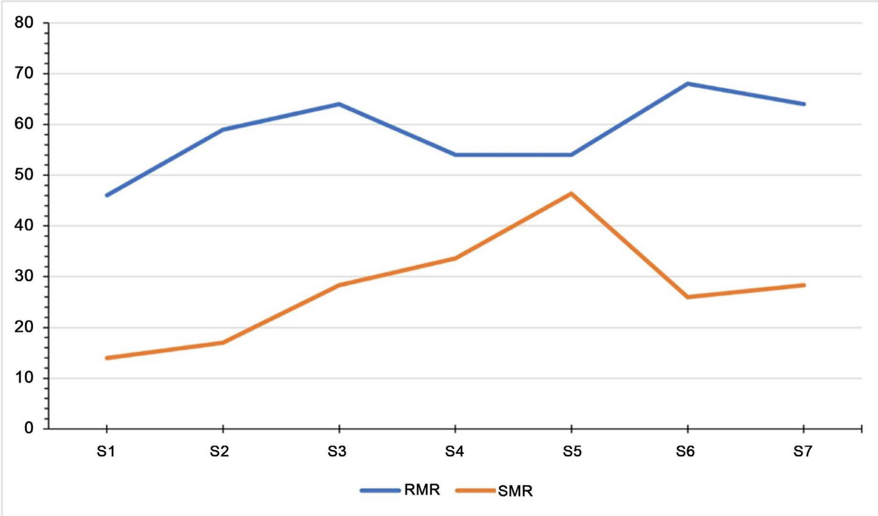

Figure 5. Graphical representation between RMR and SMR values of studied slopes.

uncertainty and frequency distribution of discontinuity orientations, as well as other controlling factors, were not quantitatively integrated. Thus, the current assessment is static and does not explicitly account for temporal variations in pore-water pressure generated by rainwater infiltration, dynamic forces associated with seismic loading, or stress and geometrical adjustments caused by road excavation. These variables might affect slope stability and should be included in future site-specific evaluations.

6. Conclusion

The results of the current study at a selected Highway stretch indicate that the rock slopes are highly vulnerable to failure and pose a serious threat to the commuters and the highway itself. Based on the study, two slopes were classified as completely unstable (class V) in the category of planar failure, four as unstable (class IV) as wedge and planar failure, and one as partially stable (class III) in the category of wedge failure. Since NH-5 is the only route connecting Shimla with the Kinnaur district of Himachal Pradesh, it is recommended to take urgent measures to prevent the partially stable to critically unstable slopes as a priority. It is also recommended to expedite the assessment of rock slopes all along the highways in the higher Himalayan region to identify vulnerable slopes for timely and appropriate action to prevent such hazards.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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