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# Stability assessment and mitigation of vulnerable slopes utilizing kinematic analysis and slope mass rating approach along Basohli-Bani Road, Kathua District, Jammu and Kashmir

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**ABSTRACT**

**Slope instability issues have a significant impact on the community's and surrounding area's socio-economic development. The current study examined the stability of sensitive rock-cut slopes in the Basohli-Bani region of Kathua district using geotechnical investigations. The study region is located in the Outer and Lesser Himalayan tectonic zones in the northwestern Himalaya. The current study's purpose was to determine the slope's stability status so that rapid mitigating measures could be recommended to avoid population losses and inconveniences. The stability assessment was conducted using rock mass characterization techniques for slope stability evaluation, such as Slope Mass Rating (SMR) classification system. Kinematic analysis was also employed to look at the various mechanisms of structurally controlled failures in jointed rock masses. The input data for the slope stability assessment was gathered through extensive fieldwork and stereonet plotting. The wedge mode of failure is the most prevalent mode, as demonstrated by kinematic analysis of the structural discontinuities. A total of thirty-two land sliding locations were considered for the cut slope stability evaluations. The SMR results show that sixteen of the thirty-two vulnerable locations are unstable, seven are completely unstable, eight are partially stable, one is stable, and none is completely stable. Site-specific mitigation strategies have been recommended for rock cut slopes that are partially stable, unstable, or completely unstable. These measures also help to mitigate the socio-economic repercussions. This study will aid ministry of road transport and highways even more because numerous civil engineering projects are now ongoing and several new ones are in the planning phases in the study area.**

**Keywords*:*** Stability assessment, RMR, SMR, kinematic analysis, mitigation.

## INTRODUCTION

The Himalayan orogeny is the consequence of the collision of Indian and Eurasian plates, and it is the greatest field laboratory on the planet for studying rock mechanics, geology, and geo hazards (Singh and Goel, 2002). Natural disasters have become far more common in recent decades. Natural disasters such as hurricanes, earthquakes, erosion, tsunamis, and landslides inflict significant loss of life and property damage to national and local governments. Landslides are a prevalent natural hazard that affects hilly locations all over the world; they have a significant impact on human lives and infrastructure. During the 1990s, landslides accounted for around 9% of all natural catastrophes globally. According to Schuster (1996), this tendency is anticipated to continue in the next decades as a result of increasing urbanization and development, ongoing deforestation, and higher regional precipitation in landslide-prone regions as a result of shifting climatic patterns. According to the Government Disaster Management Plan Report, the majority of the locations in Ladakh and J&K are very susceptible to landslides (SDMP, 2017). The frequency of landslides is growing drastically (Singh and Goel, 2002) as a result of unorganized development of different civil infrastructural works such as buildings, roads, rail network, and so on. Because of the dynamic character of the slopes, geomorphology, snowfall, intense and continuous rainfall, and continuing neotectonic activity, the hill slopes of the Lesser Himalayas are well recognized for their instability. This obviously implies that any development activity carried out in the Himalayan region requires an extensive and meticulous assessment in all aspects, otherwise it will cause major disruption and tremendous damage in terms of life, property, and the environment. The best practice in any civil engineering construction is to obtain extensive geological and geotechnical knowledge in advance in order to determine the severity of connected difficulties and, consequently, to execute mitigation measures to limit risks. Proper investigations and slope characterization are necessary for safer construction and less slope failures. The cost-benefit ratio of landslide mitigation techniques is particularly high in mountainous places across the world. These early geological and geotechnical studies on diverse rock/slope mass attributes, general geology, hydrology, and climate of the region are critical in solving such complicated geo-engineering challenges.

Slope instability in hilly places, particularly along recently cut road cuttings, has been a major concern among geoscientific groups in recent years (Sah et al., 2018; Siddique et al., 2017; Vishal et al., 2015, 2017; and Singh et al., 2010). Hoek and Bray (1981) observed that road bends, particularly in rough terrains, had a significant impact on the strength of the rock slope. In recent years, increasing anthropogenic activities appear to be a contributing cause to the instability of Himalayan slopes. According to Pantelidis (2009), the problems of instability along certain roadways are caused by inconsistencies in rock mass conditions as well as the effect of a number of external factors (environmental factors, seismic activity, anthropogenic activity, and water in the form of rainfall on slopes). In recent years, the geoscientific community has achieved remarkable progress in the field of engineering geology, and several categorization methods, such as rock mass rating 'RMR' (Bieniawski, 1973; 1979; 1984; 1989 and 1993), slope mass rating 'SMR' (Romana, 1985; Romana et al., 2003), chinese slope mass rating ‘CSMR’ (Chen, 1995), continuous slope mass rating ‘CoSMR’ (Tomás et al., 2007) and graphical slope mass rating (Tomás et al., 2012). Numerous researchers have used these classification approaches extensively for evaluating the stability of slopes (Dhiman and Thakur, 2022; Pandey et al., 2022; Jaiswal et al., 2023; Kainthola et al., 2023). These categorization systems are regarded as the backbone of major civil engineering projects and serve as a significant tool in the design sector (Duran and Douglas, 2000). As a result, it is evident that understanding the geological as well as engineering features of slope materials (rocks/soils) is critical in combating the threat of slope instabilities. The current study additionally employs a kinematic analysis approach to determine the general mechanism of failures of rock/slope mass and their trajectories (Hoek and Bray, 1981). Numerous researchers throughout the world have widely employed the kinematic approach in conjunction with RMR and SMR for slope stability study (Sharma et al., 2010).

## STUDY AREA

The research region covers parts of the Basohli (latitudes 32°30'12" N and longitudes 75°48'55" E) and Bani (latitudes 32°42'18" N and longitudes 75°48'33" E) areas in the Kathua district of Jammu and Kashmir Union Territory (Fig. 1). The research area encompasses 85 square km along the major road. The research region is identified by several key structural characteristics and water-sensitive lithologies. From north to south, the Panjal Thrust, Shali Thrust, Murree Thrust, and Main Boundary Thrust are the major structural units falling in the study area as shown in Table 1 (Choudhary, 2006; Jamwal et al., 2020). The Panjal Thrust separates the Salkhala Formation and the Punera Granite Gneiss in the research region. The Shali Thrust separates the strata of the Baila Formation and the Gamir Formation in the area under examination (Choudhary, 2006). The Murree Thrust separates the Murree Group from the Souni Volcanics. The Upper Siwalik Group is separated from the Murree Group by the Main Boundary Thrust, which is located in the southern section of the study region. The Sewa River, a tributary of the Ravi River, drains the study area, which is located between 460 and 1280 metres above mean sea level. The research region receives an average of 1672mm of rain per year, with summer temperatures averaging 18-45°C and winter temperatures averaging 2.05-20.76°C.

## METHODOLOGY

The purpose of this slope stability analysis was to determine places impacted by landslides, as well as their current and future vulnerability to landslides, and to characterize the rock mass along the road. The study region is characterized by the occurrence of several discontinuities (Fig. 2). Field investigations were conducted at thirty-two different locations (Table 2) to investigate slope stability and rock mass characteristics. The values of rock mass parameters were recorded for slope stability analysis using Romana's slope mass rating (SMR) classification system and kinematic analysis. Slope mass characterization is required for geotechnical investigations, which are based on several parameters of rock/rock mass and aim to categorize a terrain into distinct types of slope classes as well as their susceptibility to landslides, in order to offer relevant support measures.

### a) BASIC ROCK MASS RATING ($RMR_{basic}$):

To use Bieniawski's basic rock mass rating system ($RMR_{basic}$), a particular site was divided into a number of geological structural units, with each type of rock mass represented by a separate geological structural unit. The five fundamental rock mass rating parameters used for each structural unit are as follows:

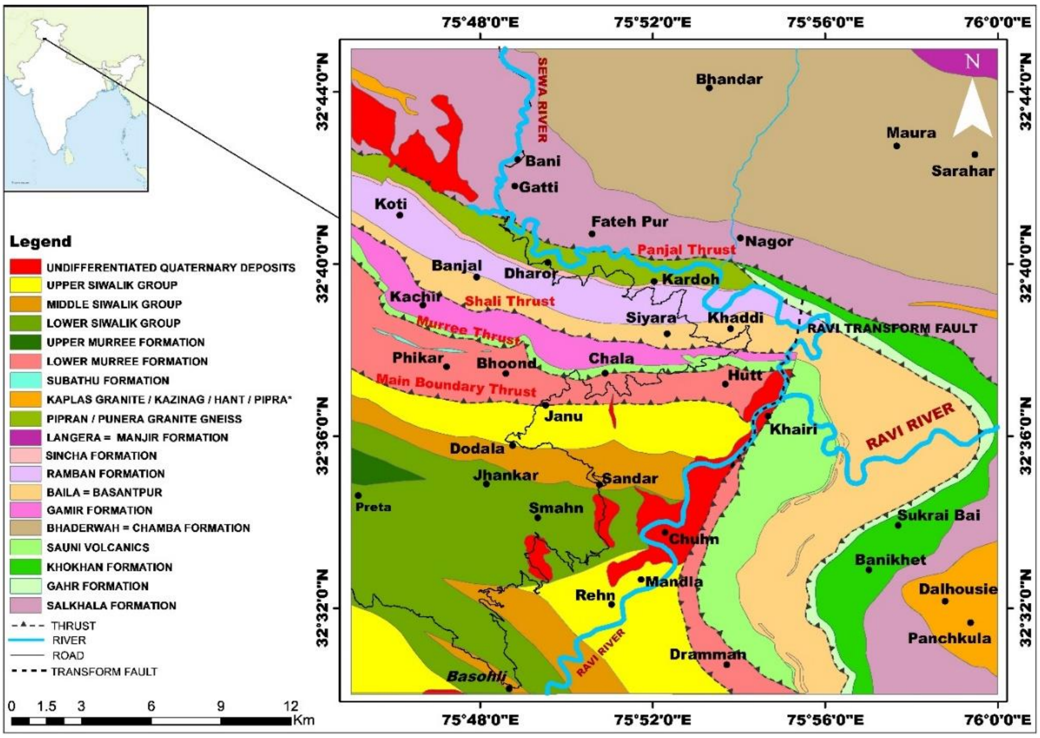


**Fig. 1:** Geological map of the study area.

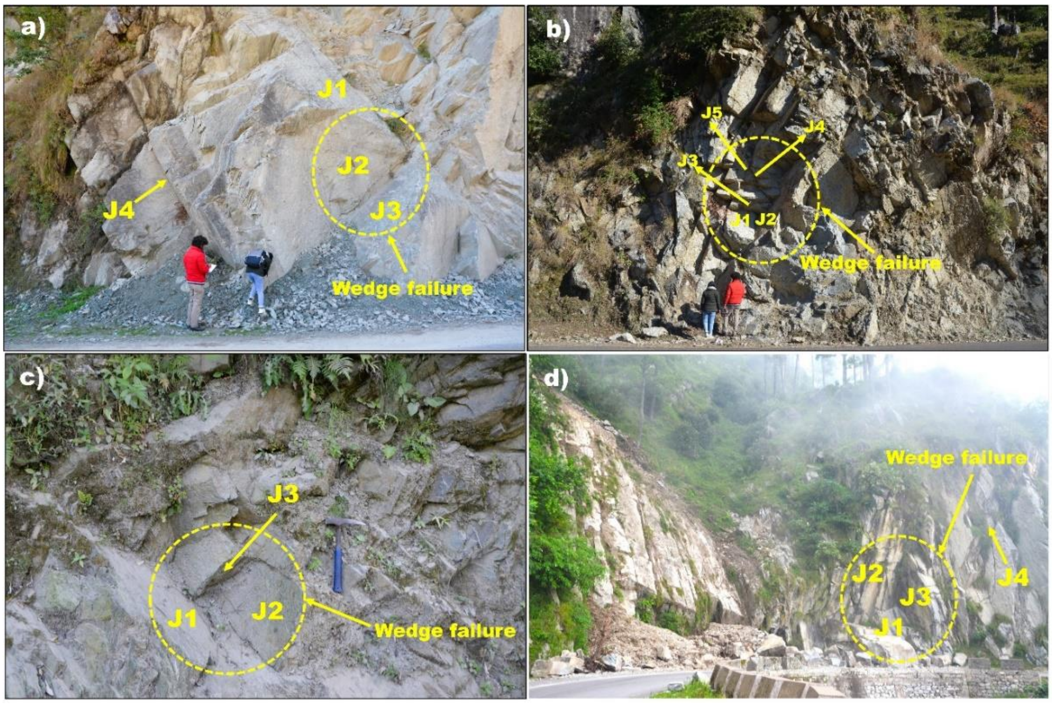


**Fig. 2:** Field photographs showing the presence of different structural discontinuities in the study area.

**Table 1.** Tectonostratigraphic setup of the study area from north to south (modified after Choudhary et al., 2006).

| Subgroup/Formation | Lithology | Age |
|---|---|---|
| Siwalik | Sandstone, siltstone, conglomerate and clay beds | Mid Miocene to Early Pleistocene |
| | ------------Main Boundary Thrust (Mundan Thrust) ------- | |
| Murree | Sandstones, shales and mudstones | Miocene |
| | --------------------------Murree Thrust-------------------------- | |
| Souni Volcanics | Green meta basalt with shale, slate and quartzite | Paleoproterozoic/Neoproterozoic?? |
| Gamir | Bands of purple shale and limestone, bands of conglomerates and cherty shales, quartzites | Neoproterozoic |
| | -----------Shali Thrust (= Sudh Mahadev Thrust) ------------- | |
| Baila | Carbonaceous slates, calcareous shale, nodular and lenticles of limestone | Neoproterozoic |
| Ramban | Bluish grey phyllitic slates, grey to dark grey shales/slates with bands of grey quartzites | Neoproterozoic |
| Sincha | Pinkish grey limestone and sandy dolomites | Neoproterozoic |
| Punera Granite Gneiss | Granite and augen gneiss | ? Palaeozoic |
| | ------------------Panjal Thrust (= Jutogh Thrust) ------------ | |
| Salkhala | Carbonaceous phyllite, schist, limestone and quartzite | Undifferentiated Proterozoic |
| Bhaderwah | Carbonaceous slate, phyllite and quartzite | Neoproterozoic |

1. **Uniaxial compressive strength/Point Load Index (PLI)**: Standard size rock samples have been taken from 32 locations, and values were acquired using a point load instrument. The equation used for calculating PLI is given below-

$$I_{L\ (50)} = P / (D.W)^{0.75}\sqrt{D_{50}}$$

where $I_{L\ (50)}$ = Point load lump strength (MPa); P = Peak load at failure in N; D =distance between point loads (mm); W = Mean width of lump (mm); and $D_{50}$ = Standard size of lump (50mm).

2. **Rock quality designation (RQD):** Palmstrom (2005) equation was used to analyse RQD-

$$RQD = 110 - 2.5\ (Jv)$$

where, Jv is a total number of joints per cubic meter and is computed from the equation given below (Palmstrom, 1982; 1996)-

$$Jv = [(1/S1) + (1/S2) + (1/S3) \ldots + (Nr/5)]$$

where, S1, S2, S3 are the joint set spacing and Nr is the number of random joints.

3. **Discontinuity spacing:** The term discontinuity covers joints, beddings or foliations, shear zones, minor faults, or other surfaces of weakness. For each set of discontinuities, the linear distance between two adjacent discontinuities should be measured and the ratings for the most critical discontinuities are obtained.

4. **Discontinuity condition:** This parameter includes-roughness of discontinuity surfaces, their separation, length or persistence, weathering of the wall rock or the planes of weakness and infilling (gouge) material.

5. **Ground water condition:** A general condition can be described as completely dry, damp, wet, dripping, and flowing. The ratings of all these parameters are given in table 3.

**Table 2.** Table showing different locations under investigation.

| Landslide site No. | Latitude | Longitude | Type of slide | Angle of reach | Formation involved in landslide |
|---|---|---|---|---|---|
| LS -1 | $32^0$35'10" N | $75^0$50'32" E | Rock slide | $70^0$-$75^0$ | Middle Siwalik |
| LS- 2 | $32^0$37'05" N | $75^0$49'56" E | Complex slide | $68^0$-$73^0$ | Lower Murree |
| LS- 3 | $32^0$37'15" N | $75^0$50'57" E | Debris slide | $64^0$-$78^0$ | Lower Murree |
| LS- 4 | $32^0$37'15" N | $75^0$51'36" E | Rock fall | $60^0$-$65^0$ | Lower Murree |
| LS- 5 | $32^0$37'47" N | $75^0$53'22" E | Rock fall | $58^0$-$63^0$ | Souni volcanics |
| LS- 6 | $32^0$37'51" N | $75^0$53'39" E | Rock fall | $70^0$-$75^0$ | Souni volcanics |
| LS- 7 | $32^0$38'30" N | $75^0$54'10" E | Rock fall | $82^0$-$86^0$ | Baila Formation |
| LS- 8 | $32^0$39'23" N | $75^0$52'47" E | Rock fall | $65^0$-$75^0$ | Ramban Formation |
| LS- 9 | $32^0$39'19" N | $75^0$52'27" E | Rock fall | $65^0$-$68^0$ | Ramban Formation |
| LS- 10 | $32^0$39'41" N | $75^0$51'29" E | Rock fall | $70^0$-$72^0$ | Punera Granite Gneiss |
| LS -11 | $32^0$39'51" N | $75^0$51'14" E | Rock topple | $75^0$-$77^0$ | Punera Granite Gneiss |
| LS- 12 | $32^0$39'48" N | $75^0$50'37" E | Rock fall | $69^0$-$72^0$ | Punera Granite Gneiss |
| LS- 13 | $32^0$39'40" N | $75^0$50'29" E | Rock fall | $76^0$-$79^0$ | Sincha Formation |
| LS- 14 | $32^0$39'41" N | $75^0$50'05" E | Rock fall | $70^0$-$72^0$ | Sincha Formation |

| | | | | | |
|---|---|---|---|---|---|
| LS- 15 | 32$^0$39'40" N | 75$^0$49'43" E | Rock fall | 62$^0$-65$^0$ | Ramban Formation |
| LS- 16 | 32$^0$39'41" N | 75$^0$49'42" E | Rock fall | 51$^0$-56$^0$ | Ramban Formation |
| LS- 17 | 32$^0$39'59" N | 75$^0$49'06" E | Rock fall | 82$^0$-85$^0$ | Punera Granite Gneiss |
| LS- 18 | 32$^0$40'07" N | 75$^0$49'04" E | Rock topple | 57$^0$-60$^0$ | Punera Granite Gneiss |
| LS- 19 | 32$^0$40'34" N | 75$^0$48'51" E | Rock fall | 58$^0$-62$^0$ | Punera Granite Gneiss |
| LS- 20 | 32$^0$40'34" N | 75$^0$48'44" E | Rock fall | 58$^0$-60$^0$ | Punera Granite Gneiss |
| LS- 21 | 32$^0$40'37" N | 75$^0$48'46" E | Rock fall | 65$^0$-67$^0$ | Punera Granite Gneiss |
| LS- 22 | 32$^0$40'39" N | 75$^0$48'46" E | Debris slide | 65$^0$-67$^0$ | Punera Granite Gneiss |
| LS- 23 | 32$^0$40'55" N | 75$^0$48'34" E | Rock fall | 59$^0$-63$^0$ | Punera Granite Gneiss |
| LS- 24 | 32$^0$41'08" N | 75$^0$48'39" E | Rock slide | 52$^0$-54$^0$ | Punera Granite Gneiss |
| LS- 25 | 32$^0$40'58" N | 75$^0$48'45" E | Rock fall | 68$^0$-70$^0$ | Salkhala Formation |
| LS- 26 | 32$^0$41'02" N | 75$^0$48'48" E | Rock fall | 68$^0$-70$^0$ | Salkhala Formation |
| LS- 27 | 32$^0$41'53" N | 75$^0$48'28" E | Rock fall | 70$^0$-72$^0$ | Salkhala Formation |
| LS- 28 | 32$^0$41'55" N | 75$^0$48'36" E | Rock fall | 50$^0$-53$^0$ | Salkhala Formation |
| LS- 29 | 32$^0$41'59" N | 75$^0$48'36" E | Rock fall | 55$^0$-60$^0$ | Salkhala Formation |
| LS- 30 | 32$^0$42'13" N | 75$^0$48'29" E | Rock fall | 68$^0$-70$^0$ | Salkhala Formation |
| LS- 31 | 32$^0$42'17" N | 75$^0$48'30" E | Rock fall | 68$^0$-73$^0$ | Salkhala Formation |
| LS- 32 | 32$^0$42'19" N | 75$^0$48'32" E | Rock fall | 70$^0$-72$^0$ | Salkhala Formation |

**b) KINEMATIC ANALYSIS:**

Markland (1972) coined the term 'kinematic analysis' and Goodman (1989) uses the term "Kinematics" to describe the movement of bodies without mentioning the forces that cause them to move. It is a useful approach for determining the likely mode of failure (plane, wedge, and topple failure) in unfavorably oriented jointed rock masses (Kumsar et al., 2000; Um and Kulatilake, 2001; Yoon et al., 2002).

**c) SLOPE MASS RATING (SMR)**:

Romana (1985) first suggested the Slope Mass Rating (SMR) technique for assessing rock slope stability. It is calculated by adding the ratings of four adjustment factors (F1, F2, F3) for the joint-slope relationship and factor (F4) depending on the type of excavation from Bieniawski's (1989) basic rock mass rating ($RMR_{basic}$) scheme. In this study, Romana's (1985; 1993) slope mass classification system has been used. The following equation is the generic formulation used to determine the SMR findings in the region under inquiry.

$$SMR = RMR_{basic} + (F1 \times F2 \times F3) + F4$$

Where $RMR_{basic}$ is the basic RMR index derived from Bieniawski's (1989) rock mass categorization and may be obtained by combining the five fundamental parameters listed above for $RMR_{basic}$; F1 is determined by the parallelism of strikes of joint and slope face; F2 is the joint dip angle; F3 shows the connection between slope face and joint's dips; and F4 is determined by the excavation process.

**RESULTS AND DISCUSSION**

The $RMR_{basic}$ values found for all 32 sites varies from 48 to 84, reflecting three rock mass classes, namely Class I-very good, Class II-good, and Class III-fair (Table 3). The lowest rating value of 48 has been obtained at LS-29, while the highest rating value of 84 was obtained at LS-12. The aggregate basic rock mass rating values for every factor indicated that of the total chosen sites, twenty-seven sites fall into the good category, accounting for 84.375% of the sites, and four fall into the fair category, accounting for 12.5% of the sites. However, just one site (site-12) comes into the very good category, accounting for 3.125% of the sites. The study also concludes that a few locations that fall into the marginal good and very close to fair categories require a closer look in terms of preventive measures to avoid becoming more vulnerable in the near future. The findings of kinematics analysis obtained by stereographic projections for 32 sites utilizing Rocscience Dip software clearly indicate the likelihood of wedge, planar, and toppling failure modes as main structural instability on slopes in the research region (Table 4). The analysis also finds that wedge mode of failure is the most common, accounting for about 63.36% of failure probability, while planar mode of failure accounts for 23.76% of failure probability and toppling mode accounts for 12.87% of failure probability in the studied region (Fig. 3). The SMR values obtained from the research region (Table 5) show that sixteen sites out of thirty-six falls into the unstable group, accounting for 50% of the analyzed sites. In contrast, seven sites (21.875% of the examined sites) are classified as completely unstable. eight of the remaining nine sites are classified as partially stable, accounting for 25% of the evaluated sites. The remaining one site is classified as stable, accounting for 3.125% of the studied locations. Figure 4 and 5 below depicts the slope stability map created for the research region. A comparison of the $RMR_{basic}$ results with the SMR index (Fig. 6) revealed that the majority of the sites falling under the good, very good and fair category under $RMR_{basic}$ fall in the unstable (LS-1, LS-2, LS-4, LS-5, LS-8, LS-12, LS-13, LS-14, LS-15, LS-16, LS-19, LS-20, LS-22, LS-24, LS-25, and LS-32), completely unstable (LS-6, LS-17, LS-23, LS-26, LS-27, LS-29 and LS-31) as well as partially stable category (LS-3, LS-7, LS-9, LS-10, LS-11, LS-21, LS-28 and LS-30) under the SMR scheme. This shows that although the rock masses of the study area fall mostly in good condition but the parallelism between the orientation of joint sets and slope is so strong that this parallelism is one of the triggering factors which is affecting the stability of the slope in the study area.

**Table 3.** The basic rock mass rating values (RMR $_{basic}$) calculated from the study area (Bieniawski, 1979).

| Landslide site no. | Ratings of rock mass: Point load index | RQD from Jv | Discontinuity spacing | Discontinuity condition | Ground water condition | RMR $_b$ value | Rock class | Rock mass quality |
|---|---|---|---|---|---|---|---|---|
| LS -1 | 20 | 20 | 10 | 10 | 15 | 75 | II | Good |
| LS- 2 | 17 | 17 | 10 | 20 | 10 | 74 | II | Good |
| LS- 3 | 13 | 13 | 10 | 20 | 15 | 71 | II | Good |
| LS- 4 | 17 | 17 | 10 | 20 | 15 | 79 | II | Good |
| LS- 5 | 17 | 17 | 10 | 10 | 15 | 69 | II | Good |
| LS- 6 | 13 | 13 | 8 | 20 | 15 | 69 | II | Good |
| LS- 7 | 13 | 13 | 8 | 20 | 15 | 69 | II | Good |
| LS- 8 | 17 | 17 | 8 | 10 | 15 | 63 | II | Good |
| LS- 9 | 17 | 17 | 10 | 20 | 7 | 71 | II | Good |
| LS- 10 | 20 | 20 | 15 | 10 | 15 | 80 | II | Good |
| LS -11 | 8 | 8 | 8 | 20 | 15 | 59 | III | Fair |
| LS- 12 | 17 | 17 | 10 | 25 | 15 | 84 | I | Very Good |
| LS- 13 | 17 | 17 | 10 | 10 | 15 | 69 | II | Good |
| LS- 14 | 17 | 17 | 10 | 10 | 15 | 69 | II | Good |
| LS- 15 | 13 | 13 | 8 | 20 | 10 | 64 | II | Good |
| LS- 16 | 17 | 17 | 10 | 10 | 15 | 69 | II | Good |
| LS- 17 | 13 | 13 | 8 | 25 | 15 | 74 | II | Good |
| LS- 18 | 17 | 17 | 10 | 10 | 15 | 69 | II | Good |
| LS- 19 | 17 | 17 | 10 | 10 | 15 | 69 | II | Good |
| LS- 20 | 17 | 17 | 10 | 10 | 15 | 69 | II | Good |
| LS- 21 | 13 | 13 | 8 | 10 | 15 | 59 | III | Fair |
| LS- 22 | 17 | 17 | 10 | 10 | 15 | 69 | II | Good |
| LS- 23 | 17 | 17 | 10 | 10 | 10 | 64 | II | Good |
| LS- 24 | 17 | 17 | 15 | 10 | 15 | 74 | II | Good |
| LS- 25 | 13 | 13 | 10 | 10 | 15 | 61 | II | Good |
| LS- 26 | 13 | 13 | 8 | 20 | 15 | 69 | II | Good |
| LS- 27 | 17 | 17 | 10 | 20 | 15 | 79 | II | Good |
| LS- 28 | 8 | 8 | 8 | 10 | 15 | 49 | III | Fair |
| LS- 29 | 13 | 13 | 8 | 10 | 4 | 48 | III | Fair |
| LS- 30 | 17 | 17 | 15 | 10 | 15 | 74 | II | Good |
| LS- 31 | 17 | 17 | 10 | 10 | 15 | 69 | II | Good |
| LS- 32 | 20 | 20 | 10 | 20 | 15 | 75 | II | Good |

**Result:** Very good = 1, Good = 27, Fair = 4, Poor = 0 and Very Poor = 0

**Table 4.** Data on joint–slope orientation and probable mode of failures of the study area.

| Landslide site no. | Slope orientation DD/DA | Joints orientation: J1 DD/DA | J2 DD/DA | J3 DD/DA | J4 DD/DA | J5 DD/DA | Probability of failure: Planar - P; Flexural Toppling - FT; Direct toppling - DT; Oblique toppling - OT; Wedge – W. |
|---|---|---|---|---|---|---|---|
| LS -1 | 105/72 | 117/69 | 046/77 | 323/42 | 308/56 | - | P-J1; W-J1 & J2; J1 & J3 |
| LS- 2 | 200/70 | 060/35 | 155/45 | 120/70 | 190/52 | - | P-J4; W-J2 & J3; J2 & J4; J3 & J4 |
| LS- 3 | 076/59 | 085/48 | 180/40 | 282/36 | 042/64 | - | P-J1; W-J1 & J2; J1 & J4 |
| LS- 4 | 210/63 | 215/56 | 062/33 | 145/69 | 040/61 | - | P-J1; W-J1 & J2; J1 & J3; J1 & J4 |
| LS- 5 | 165/60 | 184/35 | 123/78 | 050/36 | - | - | P-J1; W-J1 & J2; J1 & J3 |
| LS- 6 | 155/73 | 175/63 | 355/25 | 110/64 | 245/86 | - | P-J1; DT-J2 & J4; W-J1 & J3; J1 & J4; J3 & J4 |
| LS- 7 | 229/85 | 032/50 | 168/46 | 253/60 | 243/33 | - | FT-J1; W-J2 & J3 |
| LS- 8 | 045/75 | 350/50 | 055/86 | 125/75 | 030/70 | - | P-J4; W-J3 & J4 |
| LS- 9 | 265/68 | 235/52 | 185/15 | 045/33 | 285/65 | - | P-J4; W-J1 & J4 |
| LS- 10 | 099/72 | 049/52 | 210/52 | 152/81 | 235/12 | - | W-J1 & J3 |
| LS -11 | 325/77 | 115/65 | 031/64 | 158/46 | 217/68 | - | DT-J1 & J4; J3 & J4; OT-J1 & J2 |
| LS- 12 | 246/72 | 238/43 | 320/41 | 156/74 | 035/57 | - | P-J1; DT-J3 & J4; W-J1 & J2; J1 & J3 |
| LS- 13 | 271/79 | 284/43 | 337/44 | 133/18 | - | - | P-J1; W-J1 & J2 |
| LS- 14 | 350/72 | 009/62 | 205/15 | 294/86 | 035/75 | | P-J1; W-J1 & J3; J1 & J4 |
| LS- 15 | 115/73 | 096/70 | 180/86 | 295/38 | - | - | P-J1; W-J1 & J2 |
| LS- 16 | 130/59 | 124/56 | 195/63 | 105/14 | - | - | P-J1; W-J1 & J2 |
| LS- 17 | 345/83 | 355/79 | 280/72 | 190/78 | 285/40 | 025/64 | P-J1; W-J1 & J2; J1 & J3; J1 & J4; J2 & J5; J3 & J4; J4 & J5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| LS- 18 | 090/60 | 103/67 | 206/73 | 349/57 | 083/82 | - | DT-J2 & J3; W-J1 & J3 |
| LS- 19 | 350/60 | 010/55 | 240/74 | 268/60 | 200/78 | - | P-J1; OT-J2 & J4; W-J1 & J2; J1 & J3 |
| LS- 20 | 125/60 | 135/58 | 310/45 | 110/61 | - | - | P-J1; W-J1 & J3 |
| LS- 21 | 120/67 | 040/65 | 320/83 | 020/33 | - | - | FT-J2 |
| LS- 22 | 043/67 | 035/65 | 180/70 | 084/59 | - | - | P-J1; W-J1 & J2; J1 & J3 |
| LS- 23 | 070/63 | 130/63 | 077/58 | 040/49 | 019/72 | - | P-J2; W-J1 & J2; J1 & J3; J1 & J4; J2 & J3; J2 & J4 |
| LS- 24 | 033/54 | 073/51 | 021/64 | 351/41 | 226/24 | - | W-J1&J3 |
| LS- 25 | 350/70 | 305/45 | 210/80 | 300/85 | 010/35 | 240/15 | P-J4; OT-J2 & J3; W-J1 & J2; J3 & J4 |
| LS- 26 | 320/70 | 360/75 | 235/38 | 325/60 | 270/75 | - | P-J3; W-J1 & J3; J1 & J4; J2 & J3; J3 & J4 |
| LS- 27 | 236/72 | 241/46 | 205/84 | 043/66 | 166/74 | - | P-J1; FT-J3; OT-J2 & J3; W-J1 & J2; J1 & J3; J1 & J4 |
| LS- 28 | 135/53 | 205/68 | 270/53 | 310/12 | 275/86 | - | W-J1 & J2 |
| LS- 29 | 241/60 | 345/60 | 260/55 | 295/33 | - | - | P-J2 |
| LS- 30 | 250/70 | 305/35 | 210/80 | 280/70 | 310/85 | - | W-J1 & J2; J3 & J4 |
| LS- 31 | 250/73 | 310/45 | 260/55 | 200/65 | 356/85 | - | P-J2; W-J1 & J2; J1 & J3; J1 & J4; J2 & J3; J2 & J4; J3 & J4 |
| LS- 32 | 240/72 | 270/75 | 225/55 | 010/60 | - | - | P-J2; OT-J1 & J3; W-J1 & J2; J2 & J3 |
| **Result:** P = 24, FT = 3, DT = 5, OT = 5 and W = 64. | | | | | | | |

**Table 5.** Results of SMR obtained from the study area (Romana, 1985) where P= planar failure, W= wedge failure; FT= flexural toppling; DT= direct toppling and OT= oblique toppling.

| Landslide site no. | RMR basic | Failure | F1×F2×F3 | F4 | SMR value | Class No. | Rock mass description | Stability of particular type of failure | Probability of each type of failure | Overall Stability and probability of failure |
|---|---|---|---|---|---|---|---|---|---|---|
| LS-1 | 75 | $P_1$ | -35 | 0 | 40 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{12}$ | -50 | | 25 | IV | Bad | Unstable | 0.6 | |
| | | $W_{13}$ | -1.35 | | 73 | II | Good | Stable | 0.2 | |
| LS-2 | 74 | $P_4$ | -17.5 | 0 | 56 | III | Normal | Partially stable | 0.4 | Unstable, 0.6 |
| | | $W_{23}$ | -43.35 | | 30 | IV | Bad | Unstable | 0.6 | |
| | | $W_{24}$ | -7.65 | | 66 | II | Good | Stable | 0.2 | |
| | | $W_{34}$ | -42 | | 32 | IV | Bad | Unstable | 0.6 | |
| LS-3 | 71 | $P_1$ | -21.25 | 0 | 49 | III | Normal | Partially stable | 0.4 | Partially stable, 0.4 |
| | | $W_{12}$ | -6.3 | | 64 | II | Good | Stable | 0.2 | |
| | | $W_{14}$ | -24 | | 47 | III | Normal | Partially stable | 0.4 | |
| LS-4 | 79 | $P_1$ | -42.5 | 0 | 36 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{12}$ | -1.35 | | 77 | II | Good | Stable | 0.2 | |
| | | $W_{13}$ | -35 | | 44 | III | Normal | Partially stable | 0.4 | |
| | | $W_{14}$ | -1.35 | | 77 | II | Good | Stable | 0.2 | |
| LS-5 | 69 | $P_1$ | -29.4 | 0 | 39 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{12}$ | -6.3 | | 62 | II | Good | Stable | 0.2 | |
| LS-6 | 69 | $P_1$ | -35 | 0 | 34 | IV | Bad | Unstable | 0.6 | Completely unstable, 0.9 |
| | | $W_{13}$ | -42 | | 27 | IV | Bad | Unstable | 0.6 | |
| | | $W_{14}$ | -51 | | 18 | V | Very Bad | Completely unstable | 0.9 | |
| | | $W_{34}$ | -51 | | 18 | V | Very Bad | Completely unstable | 0.9 | |
| | | $DT_{24}$ | 0 | | 69 | II | Good | Stable | 0.2 | |
| LS-7 | 69 | $W_{23}$ | -7.65 | 0 | 61 | II | Good | Stable | 0.2 | Partially stable, 0.4 |
| | | $FT_1$ | -17.5 | | 51 | III | Normal | Partially stable | 0.4 | |
| LS-8 | 63 | $P_4$ | -35 | 0 | 28 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{34}$ | -24 | | 39 | IV | Bad | Unstable | 0.6 | |
| LS-9 | 71 | $P_4$ | -20 | 0 | 51 | III | Normal | Partially stable | 0.4 | Partially stable, 0.4 |
| | | $W_{14}$ | -9 | | 62 | II | Good | Stable | 0.2 | |
| LS-10 | 80 | $W_{13}$ | -24 | 0 | 56 | III | Normal | Partially stable | 0.4 | Partially stable, 0.4 |
| LS-11 | 59 | $DT_{14}$ | -3.75 | 0 | 55 | III | Normal | Partially stable | 0.4 | Partially stable, 0.4 |
| | | $DT_{34}$ | -0.9 | | 58 | III | Normal | Partially stable | 0.4 | |
| | | $OT_{12}$ | -3.75 | | 55 | III | Normal | Partially stable | 0.4 | |
| LS-12 | 84 | $P_1$ | -43.35 | 0 | 40 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{12}$ | -6.3 | | 77 | II | Good | Stable | 0.2 | |
| | | $W_{13}$ | -35.7 | | 48 | III | Normal | Partially stable | 0.4 | |
| | | $DT_{34}$ | -4.2 | | 79 | II | Good | Stable | 0.2 | |
| LS-13 | 69 | $P_1$ | -35.7 | 0 | 33 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{12}$ | -7.65 | | 61 | II | Good | Stable | 0.2 | |
| LS-14 | 69 | $P_1$ | -35 | 0 | 34 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{13}$ | -24 | | 45 | III | Normal | Partially stable | 0.4 | |
| | | $W_{14}$ | -24 | | 45 | III | Normal | Partially stable | 0.4 | |
| LS-15 | 64 | $P_1$ | -35 | 0 | 29 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{12}$ | -35 | | 29 | IV | Bad | Unstable | 0.6 | |

**Table 5 contd.** Results of SMR obtained from the study area (Romana, 1985; 1993) where P= Plane failure, W= wedge failure; FT= flexural toppling; DT= direct toppling and OT= oblique toppling.

| Landslide site no. | RMR basic | Failure | F1×F2×F3 | F 4 | SMR value | Class No. | Rock mass description | Stability of particular type of failure | Probability of each type of failure | Overall Stability and probability of failure |
|---|---|---|---|---|---|---|---|---|---|---|
| LS-16 | 69 | $P_1$ | -42.5 | 0 | 26 | IV | Bad | Unstable | 0.6 | Unstable,0.6 |
| | | $W_{12}$ | -35 | | 34 | IV | Bad | Unstable | 0.6 | |
| LS-17 | 74 | $P_1$ | -35 | 0 | 39 | IV | Bad | Unstable | 0.6 | Completely unstable, 0.9 |
| | | $W_{12}$ | -9 | | 65 | II | Good | Stable | 0.2 | |
| | | $W_{13}$ | -6.3 | | 67 | II | Good | Stable | 0.2 | |
| | | $W_{14}$ | -7.65 | | 66 | II | Good | Stable | 0.2 | |
| | | $W_{25}$ | -60 | | 14 | V | Very Bad | Completely unstable | 0.9 | |
| | | $W_{34}$ | -7.65 | | 66 | II | Good | Stable | 0.2 | |
| | | $W_{45}$ | -20.4 | | 53 | III | Normal | Partially stable | 0.4 | |
| LS-18 | 69 | $W_{13}$ | -7.65 | 0 | 61 | II | Good | Stable | 0.2 | Stable, 0.2 |
| | | $DT_{23}$ | 0 | | 69 | II | Good | Stable | 0.2 | |
| LS-19 | 69 | $P_1$ | -35 | 0 | 34 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{12}$ | -7.65 | | 61 | II | Good | Stable | 0.2 | |
| | | $W_{13}$ | -20.4 | | 48 | III | Normal | Partially stable | 0.4 | |
| | | $OT_{24}$ | -3.75 | | 65 | II | Good | Stable | 0.2 | |
| LS-20 | 69 | $P_1$ | -35 | 0 | 34 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{13}$ | -35 | | 34 | IV | Bad | Unstable | 0.6 | |
| LS-21 | 59 | $FT_2$ | -10 | 0 | 49 | III | Normal | Partially stable | 0.4 | Partially stable, 0.4 |
| LS-22 | 69 | $P_1$ | -42.5 | 0 | 26 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{12}$ | -6.3 | | 62 | II | Good | Stable | 0.2 | |
| | | $W_{13}$ | -7.5 | | 61 | II | Good | Stable | 0.2 | |
| LS-23 | 64 | $P_2$ | -42.5 | 0 | 21 | IV | Bad | Unstable | 0.6 | Completely unstable, 0.9 |
| | | $W_{12}$ | -20 | | 44 | III | Normal | Partially stable | 0.4 | |
| | | $W_{13}$ | -51 | | 13 | V | Very Bad | Completely Unstable | 0.9 | |
| | | $W_{14}$ | -35 | | 29 | IV | Bad | Unstable | 0.6 | |
| | | $W_{23}$ | -9 | | 55 | III | Normal | Partially stable | 0.4 | |
| | | $W_{24}$ | -42.5 | | 21 | IV | Bad | Unstable | 0.6 | |
| LS-24 | 74 | $W_{13}$ | -35.7 | 0 | 38 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| LS-25 | 61 | $P_4$ | -29.4 | 0 | 31 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{12}$ | -7.65 | | 53 | III | Normal | Partially stable | 0.4 | |
| | | $W_{34}$ | -6.3 | | 54 | III | Normal | Partially stable | 0.4 | |
| | | $OT_{23}$ | -3.75 | | 57 | III | Normal | Partially stable | 0.4 | |
| LS-26 | 69 | $P_3$ | -51 | 0 | 18 | V | Very Bad | Completely unstable | 0.9 | Completely unstable, 0.9 |
| | | $W_{13}$ | -24 | | 45 | III | Normal | Partially stable | 0.4 | |
| | | $W_{14}$ | -42.5 | | 26 | IV | Bad | Unstable | 0.6 | |
| | | $W_{23}$ | -7.65 | | 61 | II | Good | Stable | 0.2 | |
| | | $W_{34}$ | -42 | | 27 | IV | Bad | Unstable | 0.6 | |
| LS-27 | 79 | $P_1$ | -51 | 0 | 28 | IV | Bad | Unstable | 0.6 | Completely unstable, 0.9 |
| | | $W_{12}$ | -6.3 | | 72 | II | Good | Stable | 0.2 | |
| | | $W_{13}$ | -1.35 | | 77 | II | Good | Stable | 0.2 | |
| | | $W_{14}$ | -60 | | 19 | V | Very Bad | Completely Unstable | 0.9 | |
| | | $FT_3$ | -17.5 | | 61 | II | Good | Stable | 0.2 | |
| | | $OT_{24}$ | -3.75 | | 75 | II | Good | Stable | 0.2 | |
| LS-28 | 49 | $W_{12}$ | -7.5 | 0 | 42 | III | Normal | Partially stable | 0.4 | Partially stable, 0.4 |
| LS-29 | 48 | $P_2$ | -35 | 0 | 13 | V | Very Bad | Completely Unstable | 0.9 | Completely unstable, 0.9 |
| LS-30 | 74 | $W_{12}$ | -6.3 | 0 | 67 | II | Good | Stable | 0.2 | Partially stable, 0.4 |
| | | $W_{34}$ | -24 | | 50 | III | Normal | Partially stable | 0.4 | |
| LS-31 | 69 | $P_2$ | -42 | 0 | 27 | IV | Bad | Unstable | 0.6 | Completely unstable, 0.9 |
| | | $W_{12}$ | -7.65 | | 61 | II | Good | Stable | 0.2 | |
| | | $W_{13}$ | -35.7 | | 33 | IV | Bad | Unstable | 0.6 | |
| | | $W_{14}$ | -35.7 | | 33 | IV | Bad | Unstable | 0.6 | |
| | | $W_{23}$ | -60 | | 9 | V | Very Bad | Completely Unstable | 0.9 | |
| | | $W_{24}$ | -24 | | 45 | III | Normal | Partially stable | 0.4 | |
| | | $W_{34}$ | -35.7 | | 33 | IV | Bad | Unstable | 0.6 | |
| LS-32 | 75 | $P_2$ | -42 | 0 | 33 | IV | Bad | Unstable | 0.6 | Unstable, 0.6 |
| | | $W_{12}$ | -9 | 0 | 66 | II | Good | Stable | 0.2 | |
| | | $W_{23}$ | -3.6 | 0 | 71 | II | Good | Stable | 0.2 | |
| | | $OT_{13}$ | -3.75 | 0 | 71 | II | Good | Stable | 0.2 | |

**Result:** Completely unstable = 7, Unstable = 16, Partially stable = 8, Stable = 1 and completely stable = 0

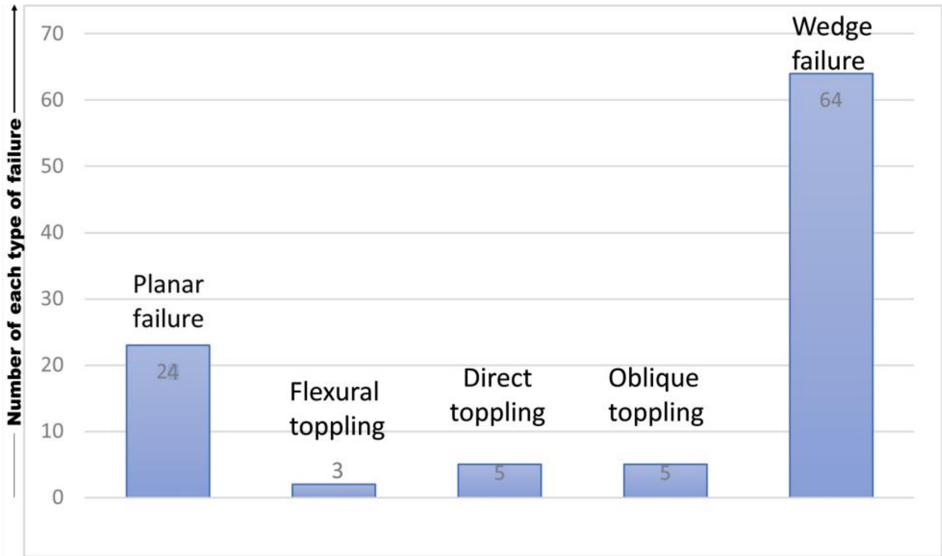


**Fig. 3:** Different types of failure modes in the study area.

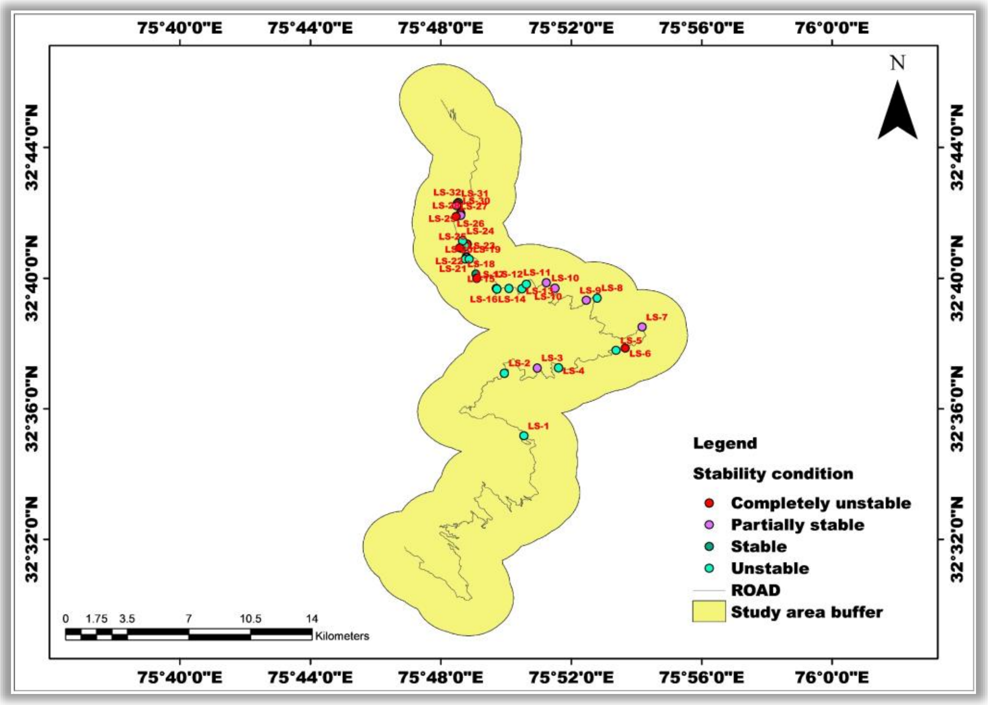


**Fig. 4:** Slope stability map of the study area.

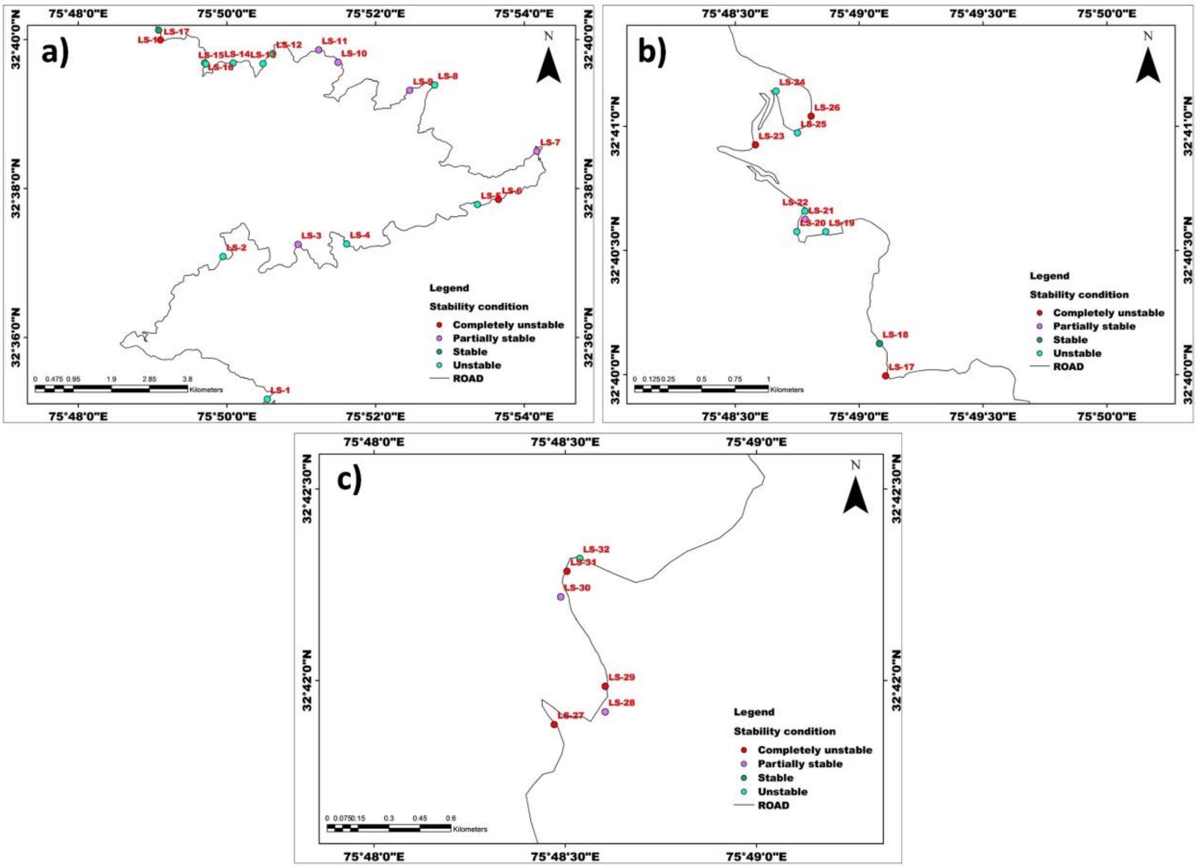

**Fig. 5 a, b and c)** Wider view of slope stability maps showing road and the stability condition of each land sliding site along the road.

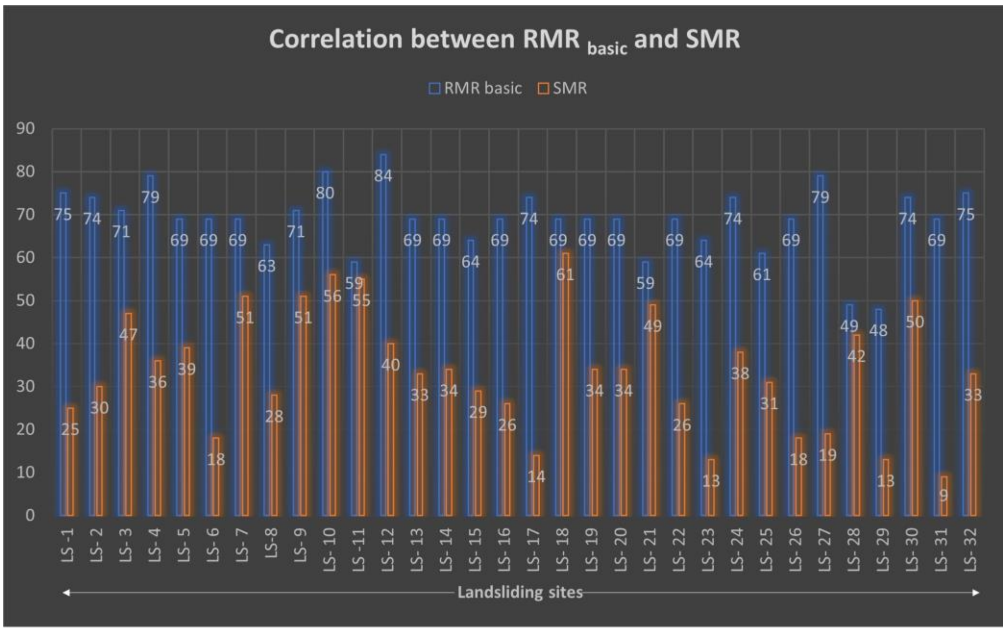


**Fig. 6:** The contrasting results evaluated through implementation of RMR $_{basic}$ and SMR.

## CAUSES OF FAILURE:

The study revealed that the occurrence of andslides in the study region was the cumulative effect of several factors. According to the research's key findings, the main causes that are reducing the stability of the slopes in the study area are wide and open apertures of the structural discontinuities, systematic toe cutting, weak lithology, high slope

**Table 6.** Mitigation measures suggested for each land sliding site (Romana, 1985)

| Site No. | Suggested mitigation measures |
|---|---|
| LS -1 | Spot bolting, toe wall and/or concrete, well developed deep drainage system |
| LS- 2 | Anchors, systematic shotcrete, toe wall and/or concrete, well developed deep drainage system |
| LS- 3 | Toe ditch and/or nets, systematic bolting/anchors, systematic shotcrete, toe wall and/or dental concrete, drainage |
| LS- 4 | Systematic bolting, wire mesh, toe wall and/or concrete, well developed drainage system |
| LS- 5 | Systematic bolting, wire mesh, toe wall and/or concrete, well developed drainage system |
| LS- 6 | Gravity or anchored wall or systematic bolts, wire mesh, toe wall and/or concrete, drainage |
| LS- 7 | Spot or systematic bolting, spot shotcrete, drainage |
| LS- 8 | Anchors, systematic shotcrete/bolting, toe wall and/or concrete, well developed drainage system |
| LS- 9 | Spot or systematic bolting, spot shotcrete, drainage |
| LS- 10 | Toe ditch and/or nets, spot or systematic bolting, spot shotcrete, drainage |
| LS -11 | Spot or systematic bolting, spot shotcrete, drainage |
| LS- 12 | Toe ditch and/or wire meshes, systematic bolting/anchors, systematic shotcrete, toe wall and/or dental concrete, drainage |
| LS- 13 | Anchors, systematic shotcrete, toe wall and/or concrete, well developed drainage system |
| LS- 14 | Anchors, systematic shotcrete, toe wall and/or concrete, well developed drainage system |
| LS- 15 | Systematic reinforced shotcrete/systematic bolting, wire mesh, toe wall and/concrete, well developed deep drainage system |
| LS- 16 | Systematic reinforced shotcrete/systematic bolting, wire mesh, toe wall and/concrete, well developed deep drainage system |
| LS- 17 | Gravity or anchored wall, toe wall and/or concrete, deep drainage |
| LS- 18 | Toe ditch or fence nets, spot or systematic bolting, drainage |
| LS- 19 | Anchors, systematic shotcrete, toe wall and/or concrete, well developed drainage system |
| LS- 20 | Anchors, systematic shotcrete, toe wall and/or concrete, well developed drainage system |
| LS- 21 | Toe ditch and/or wire meshes, systematic bolting/anchors, systematic shotcrete, toe wall and/or dental concrete, drainage |
| LS- 22 | Systematic reinforced shotcrete/systematic bolting, wire mesh, toe wall and/concrete, well developed deep drainage system |
| LS- 23 | Gravity or anchored wall, toe wall and/or concrete, deep drainage |
| LS- 24 | Anchors, systematic shotcrete, toe wall and/or concrete, well developed drainage system |
| LS- 25 | Anchors, systematic shotcrete, toe wall and/or concrete, well developed drainage system |
| LS- 26 | Gravity or anchored wall, toe wall and/or concrete, deep drainage |
| LS- 27 | Gravity or anchored wall, toe wall and/or concrete, deep drainage |
| LS- 28 | Toe ditch and/or nets, systematic bolting/anchors, systematic shotcrete, toe wall and/or dental concrete, drainage |
| LS- 29 | Gravity or anchored wall, toe wall and/or concrete, deep drainage |
| LS- 30 | Toe ditch and/or nets, systematic bolting/anchors, systematic shotcrete, toe wall and/or dental concrete, drainage |
| LS- 31 | Gravity/anchored wall or systematic bolts with wire meshes, toe wall and/or concrete, deep drainage |
| LS- 32 | Anchors, systematic shotcrete, toe wall and/or concrete, well developed drainage system |

gradient, anthropogenic activities, shear zones, absence of drainage system and highly stressed regime due to the proximity to various faults.

## SUGGESTED MITIGATION MEASURES:

The recommended mitigation measures for each location are shown in table 6.

## CONCLUSION:

Two significant empirical methodologies- SMR, and kinematic analysis, were used in this work to provide adequate conclusions on slope stability circumstances. The primary goal of using these methodologies in the research region was to gain a better understanding of the rock quality, slope stability, and likely modes and orientations of failure. SMR aided in assessing slope stability; and kinematic analysis aided in predicting the direction and mode of failures. SMR data show that the majority of the sites are in the unstable group, and kinematic analysis suggests that the wedge mode of failure is the most dominant form of failure in the study area. The variance in comparison studies of $RMR_{basic}$ and SMR values suggests that the interaction between structurally oriented discontinuities and the slope is one of the significant factors which is controlling slope instability in the study area.

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## CONFLICT OF INTEREST:

The authors declare no conflict of interest.

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