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Slope Stability Analysis and Hazards Assessment of Swat Motorway, Khyber Pakhtunkhwa, Pakistan

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Abstract. The 81-kilometer-long Swat motorway starts from the Karnal Sher Khan interchange connecting M1 motorway with Chakdara, Swat. Major part of the motorway runs through Peshawar basin, while crossing Malakand ranges at some locations. Geologically, this region belongs to weak meta morphosed rocks of Mesozoic age and consists of schist, phyllite and schistose marble. These rocks are excavated for the highway with a height ranges from a few meters to 80 meters, which requires significant stabilization measures.In this case study, slope stability of the benches along the highway have been analyzed by kinematic approach using DIPS (Rocscience software). By using the discontinuities data collected from scanline survey of the area, probability of different modes of failures are predicted and potential unstable zones are determined. Keeping in view the financial aspects, it is desired to have a hybrid stabilization technique in contrast to conventional techniques to make the slopes stable and ensure road safety. Different slope angles are analyzed and it is found that there is high chances of planar failure i.e. 43% (average)1:0.15 sloping grade, while the failure chances can be reduced to 23%, if the slope gradeis kept as 1:0.5 (63.430), which is safer enough.Moreover, the benches are highly unstable under any seismic activity.According to kinematic analysis, a data of 225 discontinuities are recorded which is divided into three sets, among them set 3 is recorded as the most critical set of discontinuities resulting in 68.7 % chances of planar failure. A hybrid stabilization system comprised of a ditch filled with sand or fine debris material and rock fall protection system is proposed, which is economical and easily constructible for slope stability at KM 37 of the Swat motorway. Keeping in view the significance and efficiency of the system, it is recommended to be adopted at other sections of the Swat motorway as well.

Keywords: slope stability, Swat motorway, kinematic approach, geological structures, hazards

Introduction

Hazard is "the probability of occurrence of a phenomenon of certain intensity in a given area and within a certain period of time". The temporal prediction of rock falls occurrence is extremely complex. Consequently,majority of the researches focus on the spatial zonation in order to quantify the relative hazards of rocks falling(Filipello *et al*., 2010).

Transportation systems such as highways are vulnerable to rock falls especially in the regions, where they cut across or skirt along mountains, plateaus, ridges and similar topographic features (Bunce *et al*., 1997) In the context of highways rock slopes, potentially unstable slopes pose risks to the traveling public, transportation infrastructure, local economies and the environment.

Slope instability is a hazardand its consequences could be very costly and may result in the loss of human lives and can may cause considerable maintenance cost for remediation, while in the dense population regions or areas prone to high velocity land slides, it can be fatal. Therefore, government and private bodies are increasingly asked about managing the "hazards" of slope instability which needs to be managed through application of the engineering (Fredlund, 2007).

Weathering of soft rock and slope instability is still not fully understood subject to the conditions despite it has been studied in various fields including geology, engineering geology, mineralogy and petrology, soil and rock mechanics. Most of the time surface weathering and local landslides occurs in soft rocks as a result, road safety is threatened at the bottom of these slopes, causing increase in maintenance cost and support system, while at the same time facilities at the top of the slopes are also endangered (Predrag and Goran, 2014).

Stability assessment of rock slopes requires comprehensive information about geology of the area such as geological structures, properties of the rock mass

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discontinuities for the structural controlled failures as well as characteristics of the rock cut faces for the raveling type failures. Other factors related to the traffic density and road designs are also required, because these have consequences to moving vehicles. The two lane Swat motorway connects Chakdara(Swat) with the Motorway 1 (M1) passing through the plain of Peshawar basin and crosses the Malakand ranges which will play a key role in the economy of the Khyber Pukhtunkhwa province. Keeping in view the importance of the rout and mass of traffic on the road, it is important to analyse the stability of slopes created in the road construction. Different authors have developed different techniques for assessing slope instability, (Youssef and Maerz, 2009; Erik, 2003). In the proposed study a suitable method is selected for the analysis and proposed recommendation based on these analyses to reduce risks to the people and increase life of the road.

Geological setting. Kilometer 37 (Km 37) is a geological cross-section of the rock strata on Swat Motorway (Fig. 1) which is approximately 270 meters and the rocks belong to late Mesozoic Kashala formation, dominated by garnet schist, schistose marble, dolomitic marble and paleozoic Karapa member of Marghazar formation that consists of calcareous phyllite, green schist, calcitic marble, dolomitic marble and coal bed.

Major part of the Km 37 is passing through the Karapa member rocks (Fig. 2). These lithologies striking in NE and dip in SE with average angle of 60 degrees, are highly fractured and jointed with few localized faults. The height of excavation varies from few meters to 60 meters with maximum of five benches to a single bench (Fig. 4).

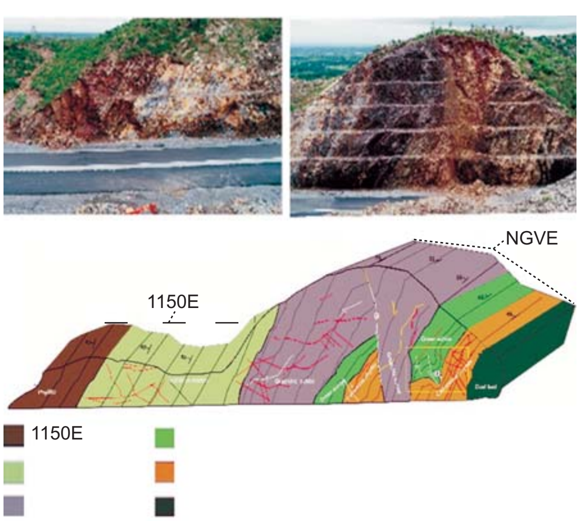


Fig. 1. Geological cross-section of the rock strata at Km 37 of Swat motorway.

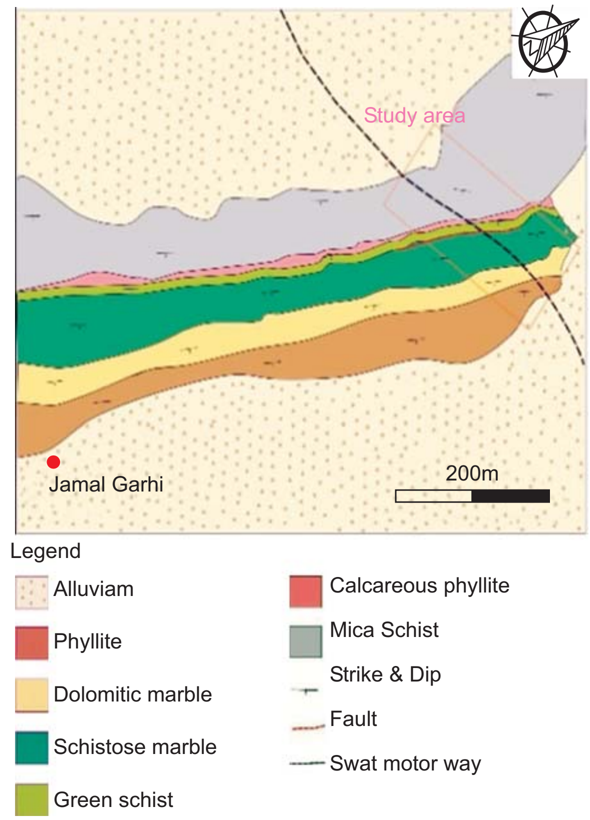


Fig. 2. Geological map of the area along the Swat motorway at Km 37 (GSP, 2004) Seismo-tectonics detail of the region.

History shows that major earthquakes have occurred along these plate boundaries in the recent past, including the earth quack of Kangra in 1905 of magnitude 8; the Quetta in 1935 of magnitude 7.6; the Makran in 1945 of magnitude 8.3; the Chamman earth quack in 1992 of magnitude 6.2; the Kashmir in 2005 with a magnitude of 7.6 and the Hindukush in 2015 of magnitude 7.5. The Peshawar basin covers over a large area of approximately 5,500 Km^2 in south-western part of the Himalayas. The basin is bounded by Khairabad fault, an equivalent of the Panjal thrust in the Kashmir Himalayas to the south and the Indus Suture zone to the north.

Internally, the Peshawar basin (Fig. 3) comprises quaternary sediments that includes fluvial gravels sands and lacustrine deposits. However, the outer fringes of

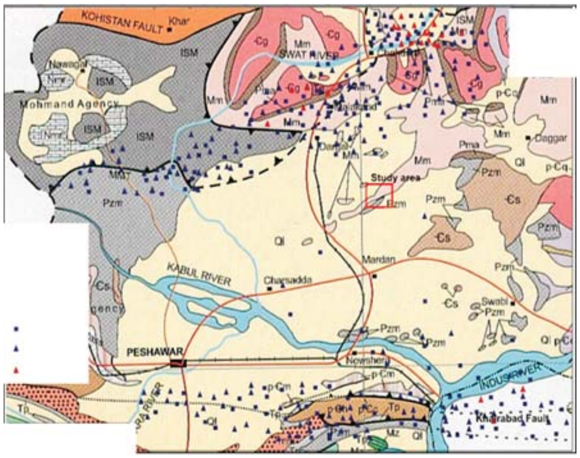


Fig. 3. Seismo-tectonics map of Peshawar basin for a period of 1904-2006 (Jan *et al.*, 2009; GSP, 2006).

Fig. 4. An overview of the Km 37 Swat motorway along the cut section showing the horizontal alignment of the road and cut slope.

the basin are predominantly fanglomerate derived from adjacent encircling mountains such as Malakand lower, Swat ranges in the north, Attock-Cherat-Dara Adamkhel ranges in the south and the Khyber ranges to the west (Kazmi and Jan, 1997; Burbank and Tahirkheli, 1985). Sediments of the Peshawar basin have been impounded by the uplifting of the Attock-Cheratrange and movement on MBT located at its southern fringes (Burbank and Raynolds, 1988).

Hydrology of the area. Fractured rock masses include numerous discontinuities with various attitudes and different scales are complicated geological media that have undergone a long period of geological evolution. The corresponding prediction and description of deformation, stress and groundwater flow in the fractured rocks are of interest in many geotechnical areas such as slope stability projects. (Xianshan and Ming, 2017). Rainfall, hydrological and geo-mechanical properties play important role in the stability of slopes. There is a need of engineering mechanics based approach by considering both current and local ground water conditions for an effective analysis of slope failure at a given location which will help in predicting the chances of slope failure (Huang *et al*., 2012).

Weak porous rocks, stores water in the small pores and spaces in it. The amount of water stored depends on the size of the rock particles. Rocks having, materials of non-uniform particle size with discontinuities withmoderate to close spacing, very narrow to tight aperture and surface staining infillings holds less water in it as compared to wide, loosely arranged particles of uniform size. This is because of the fine rock materials (such as sand and clay) settle down in the spaces between larger sized rocks materials, that reduces pores in the rock and decreases capacity of the rock to store water in it. Groundwater is found in two zones. The saturated zone, a zone in which all the pores and rock fractures are filled with water, underlies the unsaturated zone. The unsaturated zone is immediately below the land surface, contains water and air in the pores.

Water plays a prominent role in the disintegration of these clay dominant rocks. This is due to the process of freezing and thawing, drying and wetting and also through various chemical processes. This effect is manifested in the shape of decomposition of binding material of the clay rock structure and in fragmentation of the material into smaller fragments. In other words, this material is affected simultaneously by both physical and chemical weathering processes (Capparelli and Versace, 2014). No proper drainage patterns were observed at Km 37 of Swat motorway. Two drainages (nalas) exist at left and right side of the cliff, run parallel to the strike of the bed sand meet almost perpendicular to the slope face. Rain water collects in these nalas and fall at face of the cut slopes. This water contributes to seepage along the open joints, erode infilling materials and make the surface lubricated which causes failure of slopes.

Methodology. The research is completed by carrying out field tests, scanline survey and simulation detail of which is given in the following sub-sections.

Field tests. Geological hammer and point load index tests were considered at study area to evaluate the field strength of the intact rock and rock mass. Geological hammer was used for about 45 locations and point load tests were conducted for six samples of each rock type at the study area. Geological hammer tests of the mica schist, calcareous phyllite, green schist and phyllite were conducted.

Results of scanline survey are shown in Table 1 and Fig. 5, whereas contourand pole plot of the discontinuities showing major planes of the complete section of Km 37 are shown in Fig. 8-11. Moreover, Fig. 9 depicts the pole plot of the discontinuity plane as poles to observe the concentration of discontinuities on the slope surface. Detail of all these figures and tables are discussed in the results and discussion section.

Scanline joint survey. Scanline survey was used to find the required parameters of rock discontinuities for stereonetic analysis. The parameters include:

- Types of discontinuities
- Persistence
- Aperture
- Nature of infilling
- Spacing
- Roughness
- Water condition
- Lithology

Rock stability is controlled by discontinuities. Rock may fail in shape of toppling, plane failure or wedge failure depending on the geometry of discontinuities. Kinematic analysis using stereonetic projection, give the geometry of discontinuities and analyze the result to predict which types of failure is favorable to occur.

After finding the stresses in the rock samples, Roclab software was used to analyze the strength of the rock strata by applying two failure criteria i.e. Hoek & Brown criterion and Mohr-Coloumb failure criterion while scanline data was used as input in Dips software for kinematic analysis of the strata.

Results and Discussion

Scanline survey for slope stability at Swat motorway was carried out from Km 36+770 to Km 37+200 at left side of the box cut as shown in Table 1. Section of Km 37 of Swat motorway is shown in Fig. 5. At Km 36+770-36+862, weathered and sheared graphitic schist with quartz vein overlain by slightly weathered marble.Based on the Roclab analysis in Table 2, the strength parameters indicate that Schist/Phyllite ranges from very weak to weak whereas marble/schistose marble ranges from weak to medium strong. Average joints surface stained with minimum joints were filled with clay and quartz.

Geological hammer tests indicated that these lithologies fall in the weak category, while the dolomitic marble and calcitic marble show medium strength, which means the rock strata is highly degraded. Roclab® software was used to evaluate properties for analysis. Geological Strength Index (GSI) and elastic modulus & deformation modulus were obtained for both Schist and Marble samples (Fig. 7). The GSI calculated for Schist is 35 and Marble is 40. Other parameters like

Table 1. Scanline survey data for Km37

Description	Remarks
RD 36+770 to 36+862	
Persistence	1-20m
Aperture	Very narrow to tight
Infilling	Surface stain, clay, quartz
Spacing	Moderate to close
Roughness	Smooth, rough to slightly rough
Water condition	Wet to dry
RD 36+904 to 37+200	
Persistence	Moderate to high
Aperture	Narrow to tight
Infilling	Surface stain, clay, quartz
Spacing	Wide to close
Roughness	Smooth, rough to slightly rough
Water condition	Wet to dry

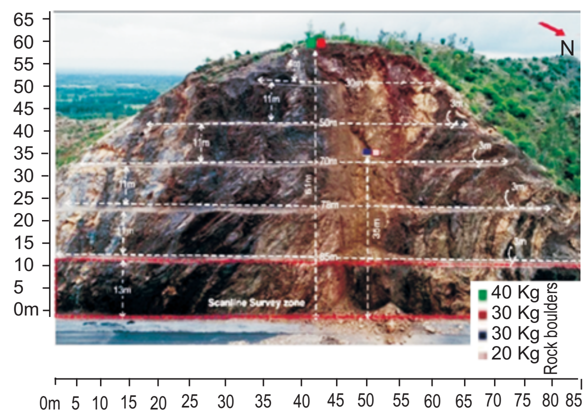


Fig. 5. Km 36+770-37+200 left side (NE direction) of box cut.

Mb, S and a are also calculated for both Schist and marble (Table 2).

Table 2. Rock strength parameters

Rock type	Parameters	Schist	Marble
Hoek & brown classification	Intact UCS (MPa)	15	110
	GSI	35	40
	Mi	10	9
	D	1	1
	Intact modulus Ei(MPa)	10125 Mpa	93500
Hoek & brown criterion	M_b	0.096	0.124
	S	1.97e-5	4.54e-5
	a	0.516	0.511
Mohr Coluomb parameters	Cohesion (MPa)	0.230	1.937
	Friction angle	11.06	12.39
Rock Mass parameters	Tensile strength (MPa)	-0.003	-0.040
	UCS (MPa)	0.056	0.662
	Global strength	0.558	4.817
	Deformation modulus, E_m (MPa)	332.46	3733.25

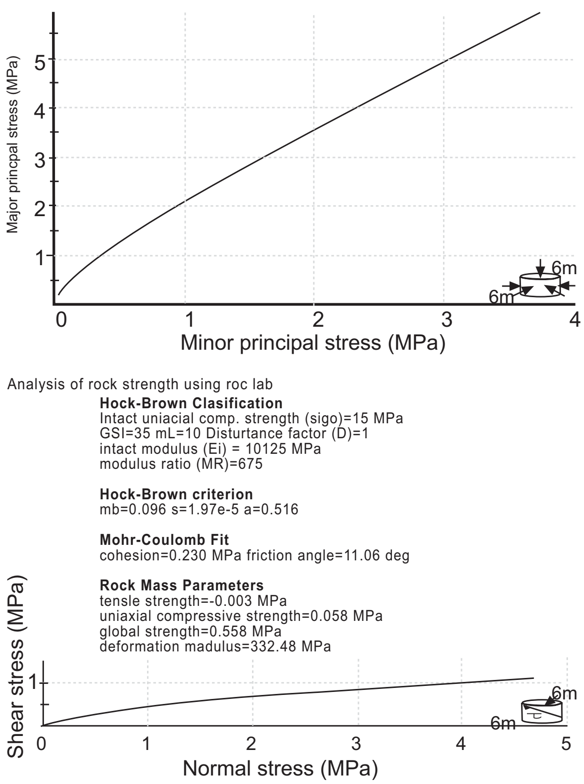


Fig. 6. Design input parameters in Roclab® for green Schist.

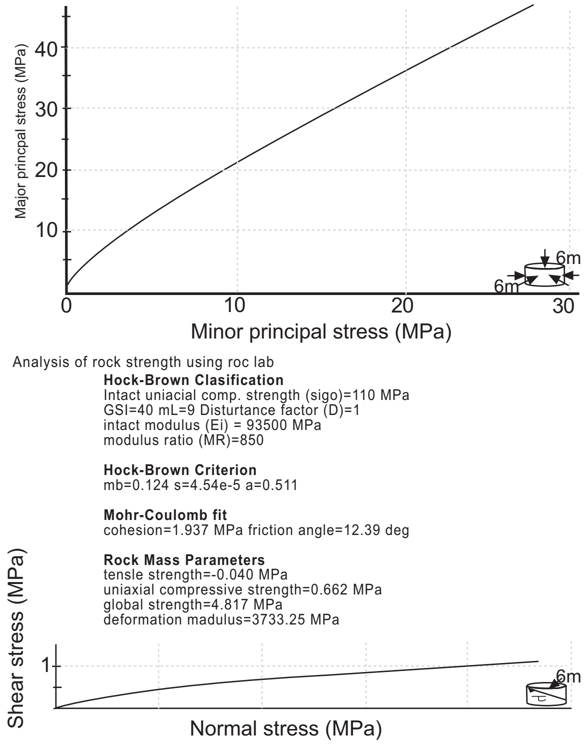


Fig. 7. Design input parameters in Roclab® for marble.

Table 3. Stereonetic analysis of the slope Km 37

	Plane failure probability %		
Description	Schist + Marble	Schist	Marble
a) Overall data			
Site slope	43%	52%	34.34%
0.25 slope	36.8%	47%	32%
0.5 slope	23%	19%	19.19%
b) 36+700-36+862			
Site slope	33%	55%	17%
0.25 slope	27.6%	45%	12.5%
0.5 slope	14%	25%	8.3%
c)36+904-37+200			
Site slope	42%	47%	41.3%
0.25 slope	37%	44.2%	37.3%

Table 4. Input Discontinuities data in Dips

Discontinuity type	No. of Discontinuities
Bedding	23
Fault	1
Joint	149
Fissure	25

Based on discontinuities concentrations, all the discontinuities were categorized into three sets of joints. Considering all the three sets of joints, the chances of plan failure at the slope was determined to be 13.78%, while set 3 being the most critical, the chances of failure were determined as 68.7% as shown in Table 5.

Stereonetic analysis. Kinematic analysis is concentrates on the use of translational failures due to the formation of wedges or planes. As such, Kinematic methods uses detailed discontinuities data to determine the existing sets of discontinuities that may contribute to rock instability. This analysis can be carried out by means of stereonet or specialized computer softwares (Erik, 2003). Rocscience software (Dips) was used to display

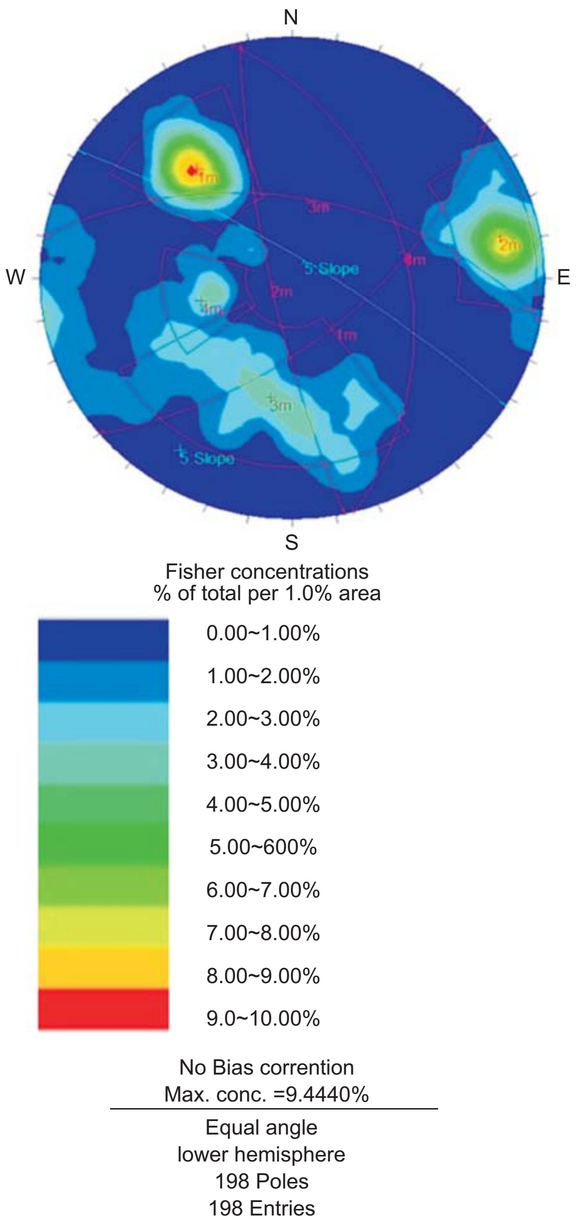


Fig. 8. Contour plot with major planes-complete section of Km 37.

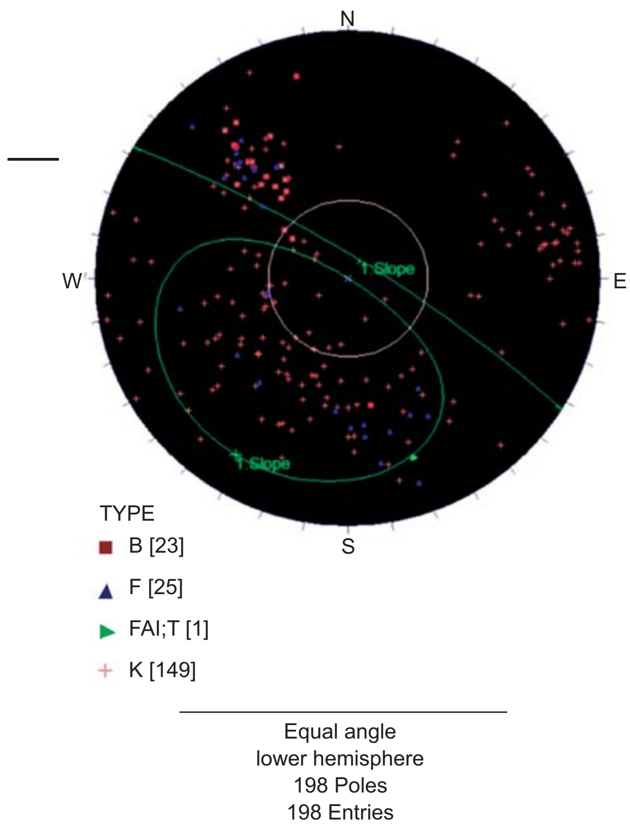
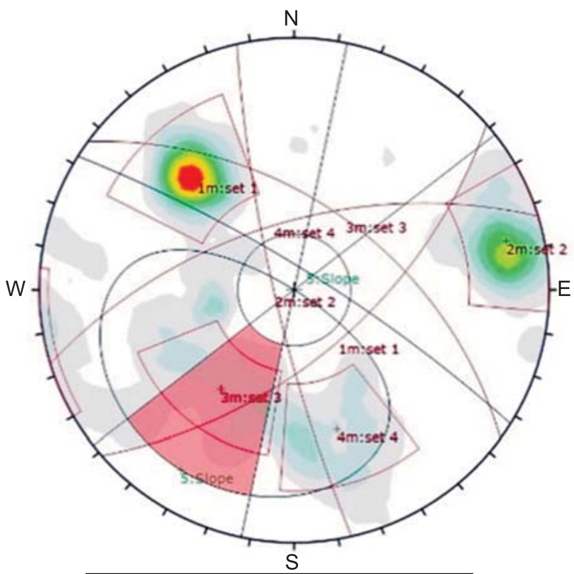


Fig. 9. Pole plot for plane failure analysis at site slope-complete section of Km.

Table 5. Kinematic analysis of sets of discontinuities for slope failure

Description	No. of discontinuities		Sets of discontinuities	Plan failure %	Wedge failure %
	Total	Critical			
Kinematic analysis (all sets of discontinuities)	225	31	3	13.78	0
Kinematic analysis (set 3)	32	22	1	68.7	0

the major planes along and across the cut slope to analyze the data for plane failure as shown in Fig. 9-11. As an input, discontinuities data were put into the Dips software as shown in Table 4, containing dip & dip direction of each discontinuity, which were plotted on the stereonet. Three types of slope angles (i.e. site slope, 1:0.25 and 1:0.5) were analyzed in the presence of the discontinuities data and the probability of plan failure were determined. The results obtained are shown in Table 3 above.This contour plot contains four joint



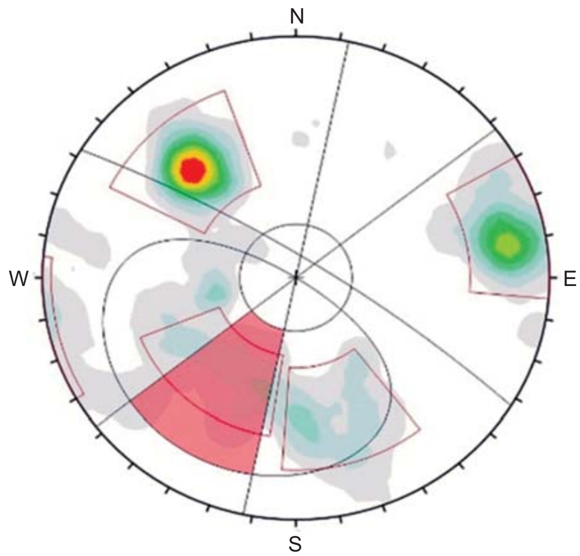
Colour	Density concentrations
	0.00 - 1.00
	1.00 - 2.00
	2.00 - 3.00
	3.00 - 4.00
	4.00 - 5.00
	5.00 - 6.00
	6.00 - 7.00
	7.00 - 8.00
	8.00 - 9.00
	9.00 - 10.00
Maximum density	9.42%
Contour data	Polo vectors
Contour distribution	Fisher
Counting cide size	1.0%

Kinematic analysis	Flanar sking
Slope dip	80
Slope dip direction	32
Friction angle	25°
Lateral units	20°

	Critical	Toral	%
Planar siding (Al)	31	225	13.79%
Panar siding (Sot 3)	22	32	GB.75%

Plot Mode	Pole vectors
Vector count	225 (225 Entries)
Hemsphere	Lower
Projection	Equal angle

Fig. 10. Stereonetic analysis for planar failure showing all sets of discontinuities.



Colour	Density concentrations
	0.00 - 1.00
	1.00 - 2.00
	2.00 - 3.00
	3.00 - 4.00
	4.00 - 5.00
	5.00 - 6.00
	6.00 - 7.00
	7.00 - 8.00
	8.00 - 9.00
	9.00 - 10.00
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	Critical	Toral	%
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Plot mode	Pole vectors
Vector count	225 (225 Entries)
Hemsphere	Lower
Projection	Equal angle

Fig. 11. Stereonetic analysis for planar failure showing slope and failure envelope.

sets which is colour coded based on the concentration of the discontinuities. Joint set 1 and 2 are more critical because of high concentration of the discontinuities as shown in the Fig. 8.

Conclusions

Slope stability of the benches along the highway have been analyzed by kinematic approach using Dips (Rocscience software). With the geotechnical data collected from scanline survey of the area, probability of different modes of failures were predicted and potential unstable zones were identified. This analysis concluded that the benches are highly unstable under any seismic activity and can cause in planar or wedge failure may lead to serious hazards especially to the traffic.

From the analysis of Roclab results, it is concluded that the rock strata is highly degraded and weak, due to which slopes are vulnerable towards failure. According to stereonetic projection analysis of the data at Km 37, there is high chances of planar failure *i.e*. 43% (average). But whenthe slope angle is reducedto 1:0.5, the chances of failure reduce to 23% which is quite safe.

To reduce the hazards of rock fall, drappingwire mesh on bench faces is recommended as a support system to reduce the velocity of falling rocks. At the toe of the slope, a ditch is suggested to be dug which will acts as rock traps and to befilled with sand or fine debris material to absorb much of the kinetic energy of the falling boulders, which will ultimately reduce the collision of the boulders with the fencing along the roadside. Catch fences or retaining wall could also be effective to increase the ditch capacity at the toe of the slope as well as road safety.

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Conflict of Interest. The authors declare no conflict of interest.

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