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Rock Slope Stability Assessment Using Geomechanical Classification and its Application for Specific Slopes along Kodaikkanal-Palani Hill Road, Western Ghats, India

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ABSTRACT

Linear infrastructure networks like roads play a vital role in the socio-economic development of hill towns centered on tourism. Stability of the slopes along the hill roads are therefore a major concern and slope failures lead to disruption of traffic and loss of property/life or both. This study analyses the stability of cut-slopes along the Kodaikkanal – Palani hill road in the Western Ghats, India using rock mass classification systems like rock mass rating (RMR), slope mass rating (SMR) and continuous slope mass rating (CSMR). These geomechanical classifications provide a preliminary assessment of rock quality based on rock strength, discontinuity properties, hydrogeological condition of the slopes and slope stability based on the inherent rock strength parameters, discontinuity orientation and method of excavation. The results showed that both rock quality and discontinuity orientation contribute to type of failure in rock slopes with RMR > 40. SMR results are conservative while CSMR classification is matches more closely to the failures obtained from the field survey. CSMR classification represents continuous slope stability conditions and hence are more suitable for development of spatial database. Cutting of roads, thereby, steepening slopes has a definite influence on the stability of slopes.

INTRODUCTION

Urban expansion and rapid tourist development in the past two decades demanded infrastructure development like expansion and widening of roads connecting the plains and the hill along the Kodaikkanal – Palani traffic corridor (Fig.1). Modification of the natural slope, either by steepening existing slopes or unplanned excavation of natural slopes for new roads make the slopes susceptible to failure. Blasting the rock slopes also weaken the slopes. Failures in rock slopes along highways in hilly terrains are a major hazard that impedes the economic development of the region, causing economic loss through property damages and increase in maintenance costs, environmental degradation as well as fatalities or injuries. A number of rock slope failures have been recorded along the Kodaikkanal – Palani highway corridor (M171), particularly at times of intense and prolonged rainfall (Fig.2). In the years 2009 and 2017, the corridor was severely affected due to rockfalls, resulting in road closure for a period of more than three days. Evaluation of rock slopes to identify the potentially unstable slopes is, therefore, mandatory for safe economic development of the region.

The most common approach to assess the stability of rock slopes and characterize rock mass is to employ geomechanical classification. Rock mass classification systems are an effective tool that helps in the assessment of the performance of rock slopes based on the structural and inherent properties of the rock mass. These classification systems consider the primary factors that affect the rock mass to assess its stability. Intact rock strength, rock quality designation index, condition, spacing and infilling of discontinuities and hydrogeological conditions are the fundamental parameter for evaluation of a rock mass.

Numerous rock mass classification systems were proposed and has been applied in engineering design and construction of foundations, tunnels and slopes. These systems provide the guidelines for design and improve the information on geological formation by quantifying them for engineering purposes. The most common rock mass rating systems are RMR (Bieniawski, 1973, 1984, 1989), Q system (Barton et al., 1974), GSI (Hoek, 1994, Hoek et al., 1995, Hoek and Brown, 1997) and RMi (Palmström, 1996, 2000, 2005). Rock mass rating was primarily developed for tunneling and underground excavation applications and have been successful in these cases. But considerable caution is required when these geomechnical classifications are to be applied to other rock engineering problems. Classification systems like rock mass strength (Shelby, 1980, 1982, Moon and Shelby, 1983), slope mass rating (Romana, 1985, Romana et al., 2003), slope rock mass rating (Robertson, 1988), rock slope deterioration assessment (Nicholson, 2002, 2003, 2004; Hack, 2002, Hack et al., 2003), falling rock hazard index (Singh 2004) and continuous slope mass rating (Tomas et al., 2004, 2006 and 2007) have been in use for the assessment of cuttings and slopes. Inspite of the availability of many classification system choices of an appropriate system for the assessment of rock slopes is difficult as local geo-environmental setup can play a major role in the stability of these slopes.

The study attempts to assess the road cuts and classify the stability of rock slopes along the Kodaikkanal – Palani hill road based on the rock mass, slope mass and continuous slope mass classification systems (Bieniawski 1973, 1975, 1979, 1989, Romana 1985, Romana et al. 2003, Tomas et al. 2004, 2006, 2007) and validate the results of the classification based on a rock slope failure database. Rock mass rating (RMR) is based on detailed field and laboratory studies while slope mass rating (SMR) and continuous slope mass rating (CSMR) includes the joint orientation with slope face and the impact of method of excavation to basic RMR. The results of SMR techniques are discrete and decision based. CSMR method is also applied to assess the stability of rock slopes as it yields results which are continuous and less discrete in comparison with the SMR method. This technique yields more accurate results than SMR as it assigns a unique value to adjustment factors for slope – joint orientation relationship, and also includes field observations and guidelines, providing a more systematic application of geomechanical classification of slopes.

STUDY AREA

The traffic corridor selected for the study lies along M171 is located in Kodaikkanal taluk, Dindigul district, Tamil Nadu (Fig. 1). The hill

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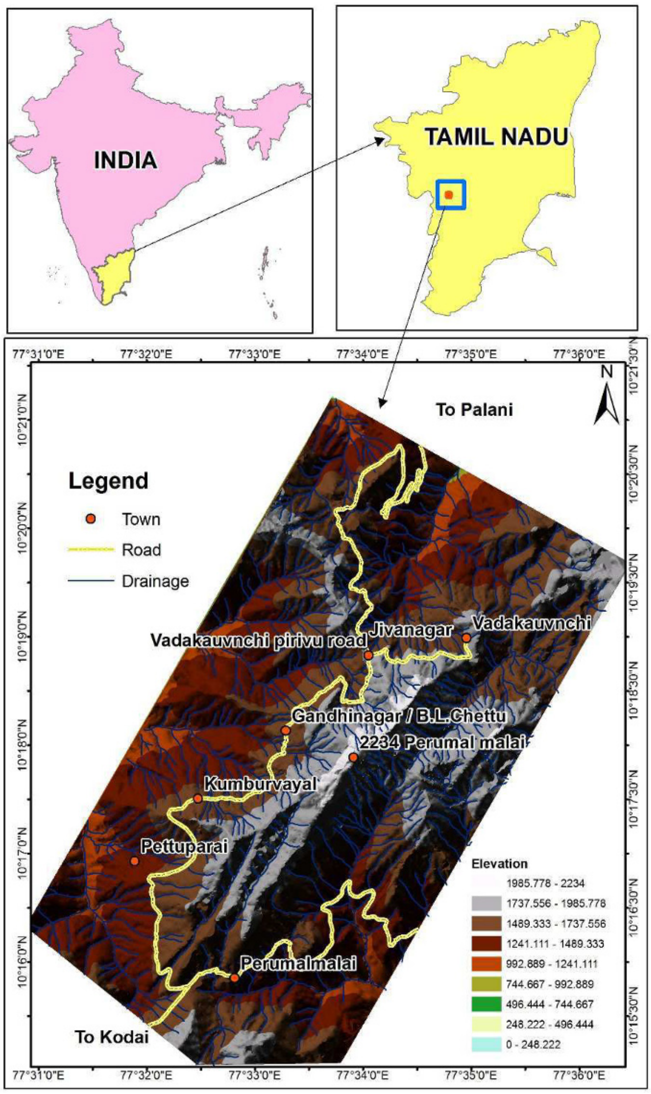

Fig.1. Location Map of the Study Area showing the Selected Road Stretch

road extends between Kumburvayal Pirivu to Vadakaunchi Pirivu, a length of 5.51 km (77°32'27.6" E and 77°34'1.2" E longitudes and 10°17'31.2" N and 10°18'50.4" N). It falls under the Survey of India Topographic map No. 58 F 11. The hill road connects the Kodaikkanal town which is a popular hill station with a large tourist influx all-round the year and Palani a prominent place of pilgrimage. The intensity and volume of traffic on this hill road is heavy owing to the proximity of these two tourist attractions. The climate is of temperate type with an average maximum and minimum temperatures of 17° - 25°C and 5° - 12°C. The temperatures are relatively even throughout the year. Figure1 shows the location map of the study area. Annual average rainfall varies from 1650 mm to 1800 mm. It is spread across most of the months in a year. Northeast monsoon (between October and early December) and southwest monsoon (between June and September) bring maximum rainfall to the region. It is comparatively dry from middle of December to March. Summer showers are experienced in April and May. Summer showers are usually intense and for short periods of time. The rainfall data was obtained from Byrant National Parkand Kodaikkanal Observatory rainfall stations. The prominent geomorphology features are dissected slopes, valleys and highly dissected plateau. Nearly 71.3% of the area is dissected slopes, followed by highly dissected plateau (27 %) and the rest a valley. The major land use categories are – plantation, cropland, settlements, forest, open scrub, waste land and water bodies. Most of the area (81.99%) falls under the plantation of various categories like cash crops, mixed trees, eucalyptus and citrus and pear. Nearly 42% of the study area is occupied by cash crop plantation followed by mixed tree plantation (24 %). Forests (deciduous, evergreen, forest plantation and open forest) occupy 9.55% of the study area.

GEOLOGICAL SETTING

The road stretch is a part of the Palani hills in northern Madurai block. The valley is a narrow strip along the road parallel to the major NE–SW trending fault. The bedrock geology of the entire road stretch is made up of charnockite of Archean age, with small patch of sillimanite cordierite gneiss. The charnockites are weakly foliated and medium grained. The maximum set of joints observed are three. The charnockite along the stretch have been slightly to highly weathered. Weathering is instrumental in causing slope instability along the selected road stretch. The rock slopes identified for the study have limited soil cover of 30 cm – 2 m on an average.

WEATHERING

The rocks are jointed and fractured and have undergone weathering to a largeextent. The joints and the original foliation make cuboidal blocks of the rocks. Exfoliation lamellae are wrapping around the blocks of charnockites and gneisses. The weathering resulted in the generation of thick soil production, which supports the plantation and vegetation. The feldspar grains are altered to clays and they found to be filling the cracks and joints at places. The soil profile shows humus soil at the top, followed by thick clayey layer with regolith formed out of feldspar bearing rocks. The lithomarge or clay are slippery and they are dirty white to white in colour with pea-sized angular fragments of rocks and quartz. Leachate of iron oxides gives red colouration to weathered rocks and soil. The feldspathic rocks show thin veinlet and clusters of feldspars and the weathering starts with initial physical weathering (i.e) differential thermal expansion and followed by chemical alteration of acidic water trickling from humus soil. The dripping water carries the clay and finer grains into the joints. Formation of clay in the joints triggers the sliding when rainfall swells the clay and makes them slippery.

METHODS

Thirty-four rock slopes were identified along the Kodaikkanal–Palani traffic corridor, between Kumburvayal and Vadakaunchi based on the history of rock slope failures, varied slope stability conditions and discontinuity characteristics. Field survey was carried out to study the orientation of the discontinuities, hydrogeological conditions and collect samples for assessment of the rock strength. Laboratory tests were carried out to evaluate the strength of rock samples according to the methods suggested by ISRM (1981).

Rock mass classification (Bieniawski, 1989) was used to calculate the RMR basic for 34 selected sections of slopes along the Kodaikkanal – Palani hill road summing the rating for five basic geomechanical rock and discontinuity condition parameters. Table 1 shows the rock mass classification system rating for the selected rock slopes after Bieniawski (1989). The total RMR value ranges between 0 – 100.

Slope mass rating (Romana, 1985; Romana et al., 2005) was calculated using RMR_{basic} and the adjustment factors for discontinuity orientation and method of excavation. Adjustment factors F1, F2 and F3 depend on the discontinuity – slope orientation and also take into account the type of failure (planar, wedge or toppling) while F4 depends on the mode of excavation of slope. The SMR values describe the stability of the slope through a range of values between 0 – 100. Table 2 shows the SMR values for the five stability classes. However, these represent the slope stability condition only for the discrete sections considered.

In order to represent the stability conditions of the slope continuously along the stretch, continuous slope mass rating (Tomas

Table 1. RMR Classification for the Selected Slope Sections

Slp. Rep.	UCS	RQD	Spacing of Disconti-nuities	Condition of disconti-nuities	Ground water	RMR_{basic}	Rock Quality
1	7	17	5	25	15	69	Good
2	12	13	5	30	7	67	Good
3	12	17	20	0	7	56	Fair
4	12	20	20	30	7	89	Very Good
5	12	20	15	10	7	64	Good
6	12	20	15	20	7	74	Good
7	12	20	5	25	4	66	Good
8	12	20	8	30	4	74	Good
9	12	20	10	10	4	56	Fair
10	12	20	15	30	4	81	Very Good
11	12	20	15	0	15	62	Good
12	12	20	10	30	4	76	Good
13	7	8	5	0	4	24	Poor
14	2	8	5	10	0	25	Poor
15	12	8	5	10	7	42	Fair
16	7	8	15	0	7	37	Poor
17	7	20	8	25	7	67	Fair
18	4	20	10	0	7	41	Fair
19	7	20	8	0	7	42	Fair
20	12	20	8	30	15	85	Very Good
21	12	20	8	30	7	77	Good
22	7	17	8	10	15	57	Good
23	12	17	10	25	15	79	Good
24	12	20	8	10	7	57	Fair
25	12	17	8	0	7	44	Fair
26	12	20	10	30	7	79	Good
27	12	20	10	0	7	49	Fair
28	12	20	10	30	15	87	Very Good
29	12	20	8	30	15	85	Very Good
30	12	20	15	30	15	92	Very Good
31	12	20	10	0	7	49	Fair
32	12	20	10	30	15	87	Very Good
33	12	17	8	0	15	52	Fair
34	12	17	8	0	15	52	Fair

Slp. Rep. – Slope Representation

et al. 2004, 2006, 2007) was calculated. Adjustment factors F1 and F2 have been modified from that of SMR by using the best fit of the discrete values and a new continuous function has been proposed for F3 (Tomas et al. 2007). The factor F4,which considers the mode of the excavation is not altered and remains the same as in the SMR (Romana 1985, Romana et al. 2005). Stability classes of the slopes and the probability of their failure of SMR classification systemare also applicable for CSMR classification. The results from RMR, SMR and CSMR geomechanical classification systems are compared with the known locations of failure along the selected road stretch along Kodaikkanal – Palani hill road for validation.

RESULTS AND DISCUSSION

Detailed geological investigations were carried to study the discontinuity orientation, its spacing & condition and ground water conditions (hydrogeology) through the use of geomechanical classifications – RMR, SMR and CSMR. There are outcrops of rock along the road sections and these were used to determine the geologic discontinuity, weathering conditions and structural characteristics of the rock slopes.

Field survey showed that the road stretch comprised of alternative lengths of massive rock slopes, weathered slopes and soil slopes. Natural rock slopes are normally blasted to form cut slopes. Slope height varies from 2.5 m to 15 m and the gradient of the cut-slopes vary between 36° and 77°. The minimum soil cover on most of the slopes is about 30 cm and a maximum thickness of 2 m is observed on highly weathered slopes. Failures are common on slopes of height more than 7 m particularly more in slopes of height 12 m. Wedge, planar and toppling failures are observed in the rock slopes investigated. Failures in the rock slopes were controlled by the structure and hydrology. Degree of weathering and unconfined compressive strength of the rock also contribute to slope failures.

Table 2. Stability Class according to Romana (1985)

Class	I	II	III	IV	V
SMR Range	81 – 100	61 – 80	41 – 60	21 – 40	0 – 20
Description of Slope	Very good	Good	Normal	Bad	Very Bad
Stability	Completely Stable	Stable	Partially Stable	Unstable	Completely Unstable

Condition of Discontinuities

Joint formation in the area is due to topography and load. Foliation trend is generally between 30°and 60°, along the north east direction with south-easterly dip of about 65° – 85°. The joints have different orientation pattern with north eastern strike and westerly dip north of BL shed area. A set of joints with an east-west orientation and southern dip are observed near BL shed area. Near Kumburvayal, one set of joints have a northwest orientation with north eastern dip and another set with southwestern dip. The general trend of the road is along northeast and the joints dipping towards the road are prone to failure.

Predominantly there is a single set of joint, but there are up to 3 sets of joints in the region. The joints in the region are open and closely spaced with a joint spacing of less 60 mm. The minimum and maximum joint spacing is 1 mm to 100 mm respectively. Few joints in the region are also closed. The rocks are prone to failure along the joint planes owing to the minimum aperture size of the joints. Weathered rock material fills the joints in most places. Clay infilling is present in highly weathered sections making them more prone to failure, particularly during periods of precipitation. Persistence varies from 0.1 to 1. The average persistence is 0.7 and this indicates that the rocks are highly jointed.

Hydrogeology

Observation on hydro-geology of cut-slopes show that most slopes are wet. Few slopes are also in dripping and flowing conditions. The wetness of the slope can be attributed to the general topography of the area. Most of the joints are wet. Joints east of Kumburvayal are in dripping condition and north of BL shed, flowing condition exist in the joints.It is to be noted that the stability of the slopes will change with the change in the hydro-geological condition, especially during intense periods of precipitation.

RMR Classification

Rock mass rating is a simple method of representing rock mass quality in an effective way by simple arithmetic algorithm. Bieniawski's (1989) rock mass classification was used to assess the geomechnical strength of the rock. The five parameters that determine the stability of the slope are: the uniaxial compressive strength, rock quality designation (RQD), spacing and condition of discontinuity and ground water conditions (Bieniawski, 1989). Uniaxial compressive strength (UCS) of intact massive rock along the selected traffic corridor is 200 MPa on average and that of weathered rock specimen is 23 MPa. The average UCS along the selected road stretch was 150 MPa. The rock quality designation (RQD) values were calculated using the joint volume count. Limited field verification was done in areas of weathering where the RQD values of joint volume count are higher. Rock type remaining almost the same in the selected road stretch, significant changes in discontinuity characteristics control the stability of the slope. Ground water parameter takes into account the occurrence of water along the discontinuities (Ferrari et al., 2014). It is observed that most slopes exhibit wet to flowing conditions, making them susceptible to instability.

The RMR values range from 15 to 92 along the selected stretch, 53 % of the rocks along the stretch areof very good and good quality while 38% of the slopes are in fair condition and the remaining are in poor condition (i.e.) highly susceptible to failure. RMR value greater than 40 indicates the stability of the slopes is governed both by the orientation of the discontinuity and shear strength of the discontinuities (Robertson, 1988), which is the case in 91 % of the rocks along the stretch. But when RMR value is less than 30 (for 9 % of the slopes), the failure is inevitable in the rock mass (Robertson 1988). The susceptibility to failure will change with the change in the groundwater condition (i.e.) the region is a hilly terrain and is dissected by a number of first order streams and in the rainy season the groundwater conditions change from dry or wet to dripping or flowing increasing the chances of failure. The results of the RMR classification indicate that the majority of the slopes are of considerable strength and less prone to failure, but recurring failures along the 9% of the vulnerable slopes necessitates a study on its stability criteria in addition to the quality of the rock mass.

SMR Classification

RMR classification system accounts for the strength and deformability of a rock mass, indicating its competence as a geologic material (Abishek Kumar Chaurasia et al., 2017). Slope mass rating (Romana, 1985, Romana et al., 2003, Sarkar et al., 2015) is also a rock mass classification method based on RMR classification but is modified with adjustment factors, F1, F2 and F3 to account for the influence of adverse joint orientation and F4 for the method of excavation. Adjustment factors F1, F2 and F3 depend on the geometrical relationship between the discontinuities that affect the rock and the slope (Tomas et al. 2007). Adjustment factor F1 which depends on the parallelism between joint and slope face, for 73.5% of the slopes under study is very favourable while for 14.8% it is very unfavourable. Factor F2 is a measure of probability of joint shear strength and 38.2% of the slopes fall in the very unfavourable category and 2.9% in the very favourable category. F3 relates the slope and joint dips and 67.6% of the slopes fall under very unfavourable category. All the cut-slopes have been blasted, therefore, F4 was assigned a value of 0.

Sample stereographic projection to estimate the probable mode of failure of the cut-slope is described below explaining the computation of SMR for the joint planes with the maximum probability of failure. In case of wedge failure, the plunge direction of the line of intersection formed by discontinuities with a strike / dip of slope direction is considered (Hoek and Bray 1981, Sarkar et al. 2012). For example, consider slope representation number 14 in Table 3, there are two major discontinuity planes. The discontinuity and slope orientation are:

J1 – 190/23 NW; J2 – 105/70 NE; Slope – 56/73 NW
Plunge of line of intersection – 293/23 NW.
J1 is the critical joint, but as the type of failure is a wedge (Singh and Goel, 1999) direction of the intersection of plunge is used.
α_j - α_s= 243 – 56 = 187 ; F1 = 0.15
β_j = 23; F2 = 0.4
β_j - β_s = 23 – 73 = -50; F3 = -60
F4 = 0 (Slope formed by normal blasting)
where α_s – slope strike; α_j – joint strike; β_s – slope dip; β_j – joint dip
F1, F2 and F3 were obtained from the Romana et al. (1985) and Romana et al. (2003) based on the joint orientation.
RMR = 25; SMR = RMR + (F1*F2*F3) + F4 = 21

Field photograph and stereo-plot for an unstable cut-slope section is shown in Fig.2. The type of failure is observed to be wedge failure. In this example, SMR value of 21 falls under class IV indicating the slope is unstable. Field survey shows that the slope has already failed and there is still potential for failure during periods of intense precipitation.

Table 3. SMR Classification of Selected Slopes

Slp. Rep.	F1	F2	F3	RMR	SMR	Class	Stability
1	0.15	1	-60	69	60	Normal	Partially Stable
2	0.7	1	-6	67	63	Good	Stable
3	0.15	1	0	56	56	Normal	Partially Stable
4	0.15	1	-6	89	88	Very Good	Completely Stable
5	0.15	1	-60	64	55	Normal	Partially Stable
6	0.15	0.4	-60	74	70	Good	Stable
7	0.15	1	0	66	66	Good	Stable
8	0.15	1	-6	74	73	Good	Stable
9	0.15	0.85	-60	56	48	Normal	Partially Stable
10	0.15	0.4	-60	81	77	Good	Stable
11	0.15	1	0	62	62	Good	Stable
12	0.4	1	-60	76	52	Normal	Partially Stable
13	0.15	0.4	-60	24	20	Very Bad	Completely Unstable
14	0.15	0.4	-60	25	21	Bad	Unstable
15	1	0.4	-60	42	18	Very Bad	Completely Unstable
16	0.4	0.7	-60	37	20	Very Bad	Completely Unstable
17	0.15	0.4	-50	67	64	Good	Stable
18	0.15	0.7	-60	41	35	Bad	Unstable
19	0.15	0.4	-60	42	38	Bad	Unstable
20	0.15	0.4	-60	85	81	Very Good	Completely Stable
21	0.15	0.4	-60	77	73	Good	Stable
22	0.15	0.4	-60	57	53	Normal	Partially Stable
23	0.15	1	0	79	79	Good	Stable
24	1	1	0	57	57	Normal	Partially Stable
25	1	0.4	-60	44	20	Very Bad	Completely Unstable
26	1	0.4	-60	79	55	Normal	Partially Stable
27	0.15	0.85	-60	49	41	Normal	Partially Stable
28	0.15	0.7	-60	87	81	Very Good	Completely Stable
29	0.7	0.15	-60	85	79	Good	Stable
30	0.15	0.85	-60	92	84	Very Good	Completely Stable
31	1	0.4	-60	49	25	Bad	Unstable
32	0.15	0.4	-60	87	83	Very Good	Completely Stable
33	0.15	1	0	52	52	Normal	Partially Stable
34	0.15	1	0	52	52	Normal	Partially Stable

Slp. Rep. – Slope Representation; F1, F2 and F3 are Romano (1985) adjustment factors that depend on the discontinuity – slope orientation. F4 = 0 as all slopes are blasted normally.

Lower the SMR value, more unstable the cut-slope is. SMR value ranges from 18 to 88 (Table 3). All the slopes with an SMR value below 40 have already failed. SMR shows that nearly 55.9 % slopes are susceptible to failure (i.e) falls under partially stable to completely unstable category in contrast to the RMR classification which indicated that only 9 % of the slopes are vulnerable. Field survey shows that slopes falling under the partially stable category have failed in 45.5 % of the locations and the condition of stability worsens with the increase in wetness of the slope. Figure 2shows some of the failed slope sections observed in the field. It is observed that rock slope failures can be expected during rainy season when the ground water condition on cut-slopes change from dry or wet condition to dripping or flowing condition.

SMR does not include the height of slopes and is conservative. SMR gives the stability of the specific slope section meaning that the values are discrete and cannot be extended to the sections. Classification of slopes based on SMR is suitable for a preliminary assessment of the nature and stability of slopes and a detailed deterministic approach is required to obtain a factor of safety for design purposes.

CSMR Classification

Remedial measures for vulnerable slope sections are effective when the slope stability classification describes the continuous sections of the slope. But both RMR and SMR are discrete classifications and this can cause significant changes in the quality of the rock mass with a small change in even one of the parameters (Tomas et al. 2007) affecting the final classification output of the slope. CSMR (Tomas et al. 2007, Umrao et al. 2011, Sarkar et al. 2015, Sarkar et al. 2016) is

Table 4. CSMR Classification of Selected Slopes

Slp. Rep.	F1	F2	F3	RMR	SMR	Class	Stability
1	0.12	0.92	-58.22	69	62	Good	Stable
2	0.85	0.97	-4.93	67	63	Good	Stable
3	0.15	0.98	-1.98	56	56	Normal	Partially Stable
4	0.14	0.98	-2.16	89	89	Very Good	Completely Stable
5	0.12	0.92	-58.55	64	57	Normal	Partially Stable
6	0.12	0.38	-58.49	74.	71	Good	Stable
7	0.13	0.97	-1.75	66	66	Good	Stable
8	0.13	0.98	-2.18	74	74	Good	Stable
9	0.12	0.78	-59.20	56	50	Normal	Partially Stable
10	0.26	0.78	-58.33	81	69	Good	Stable
11	0.15	0.97	-1.34	62	62	Good	Stable
12	0.54	0.93	-58.88	76	46	Normal	Partially Stable
13	0.12	0.38	-59.31	24	21	Very Bad	Completely Unstable
14	0.12	0.33	-59.32	25	23	Bad	Unstable
15	1.09	0.35	-59.31	42	19	Very Bad	Completely Unstable
16	1.10	0.38	-59.19	37	12	Very Bad	Completely Unstable
17	0.12	0.59	-56.32	67	63	Good	Stable
18	0.12	0.41	-59.28	41	38	Bad	Unstable
19	0.12	0.27	-59.33	42	40	Bad	Unstable
20	0.12	0.35	-59.22	85	82	Very Good	Completely Stable
21	0.13	0.30	-59.24	77	75	Good	Stable
22	0.12	0.30	-59.31	57	55	Normal	Partially Stable
23	0.17	0.98	-1.01	79	79	Good	Stable
24	1.17	1.00	-0.40	57	57	Normal	Partially Stable
25	0.95	0.41	-59.19	44	21	Bad	Unstable
26	1.17	0.30	-59.30	79	58	Normal	Partially Stable
27	0.12	0.20	-59.40	49	48	Normal	Partially Stable
28	0.14	0.59	-57.92	87	82	Very Good	Completely Stable
29	0.54	0.20	-59.22	85	79	Good	Stable
30	0.11	0.20	-59.40	92	91	Very Good	Completely Stable
31	1.16	0.27	-59.36	49	30	Bad	Unstable
32	0.12	0.27	-59.16	87	85	Very Good	Completely Stable
33	0.33	1.00	-0.40	52	52	Normal	Partially Stable
34	0.33	1.00	-0.40	52	52	Normal	Partially Stable

Slp. Rep. – Slope Representation; F1, F2 and F3 are Tomas et al. (2007) adjustment factors that depend on the discontinuity – slope orientation. F4 = 0 as all slopes are blasted normally.

an improvement over the SMR classification system. The most significant improvement is the application over continuous slope sections instead of specific sections as in SMR. The adjustment factors F1 and F2 are modified and a new continuous function was derived for the factor F3 from continuous curves (Tomas et al. 2007). The CSMR classification of the selected road stretch shows that 61.8 % of the slopes are very favourable and 14.8 % of the slopes are very unfavourable, considering the factor F1 but the dip of joint is critical in nearly 35.3 % of the slopes and no slope is very favourable (based on adjustment factor F2). The relation between slope face and dip of joint (F3) is very unfavourable in70.6 % of the slopes. CSMR values range from 12 to 91 (Table 4). CSMR classifies 53 % of the slopes under vulnerable category, and field observation shows that 38.2% of the identified slopes have already failed. This fact demonstrates that CSMR assesses the stability of a slope more accurately, in line with the field conditions than SMR (Sarkar et al., 2015, Sarkar et al., 2016).

A model explanation of the calculation for deducing the adjustment factors F1, F2 and F3 is shown below. The CSMR classification of the slope representation number 31 is considered.

$$F1 = \frac{16}{25} - \frac{3}{500} \arctan(0.1\,|\alpha_j - \alpha_s| - 17) = 0.12$$

$$F2 = \frac{9}{16} + \frac{1}{195} \arctan(0.17\,\beta_j - 5) = 0.33$$

$$F3 = -30 + \frac{1}{3} \arctan(\beta_j - \beta_s) \text{ for wedge and planar failure.}$$

$$F3 = -59.32$$

$$CSMR = RMR_{basic} + (F1.F2.F3) + F4 = 23$$

CSMR classification shows that this slope falls under class 4 (Table 4), which is an unstable category. Figure 3 shows that in most cases the stability of the slopes assessed by SMR and CSMR reflected the rock mass quality determined by RMR. But in a few cases, especially when RMR is greater than 40, slopes are highly susceptible to instability (slope representations 15, 18, 19, 25 & 31) irrespective of the basic RMR value. This emphasizes the importance of unfavourable discontinuity orientation in causing a slide. Factor F3 is observed to be the most critical factor in causing the failure of slopes. This implies that road cutting activity and steepening the slopes is the most important cause of slope failures. Further, rock slopes with RMR less than 30 are unstable with highly fragmented structure and poor surface conditions. Their susceptibility to failure is by virtue of the inherent rock mass quality. In the present case study, all slopes with RMR less than 40 have failed. Similarly, rock slopes with RMR more than 60 are stable irrespective of their discontinuity orientation. This range of RMR represents blocky to very blocky structure (Sarkar et al., 2012) and good surface condition of the rock mass. Stability, is thus not governed by the strength or discontinuity characteristics of the rock mass but by both. Of the 34 slopes assessed 19 slopes are stable under SMR classification system and 18 under CSMR classification system. This difference between the two classification system may not appear significant, but the sensitivity of CSMR can be observed in the

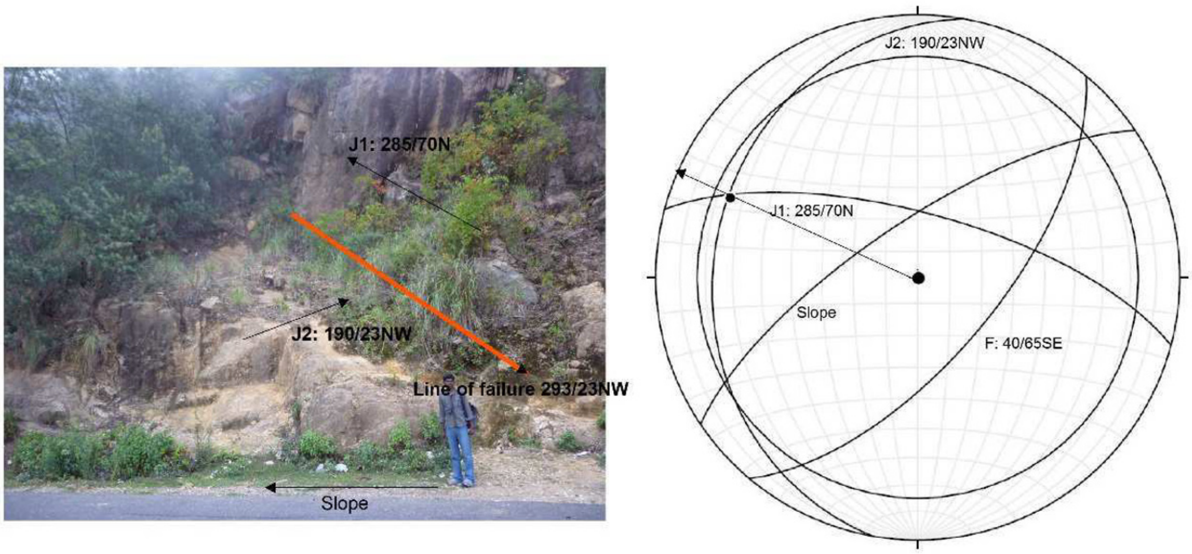

Fig.2. Stereo-Plot and Field Photo of Slope with Wedge Failure

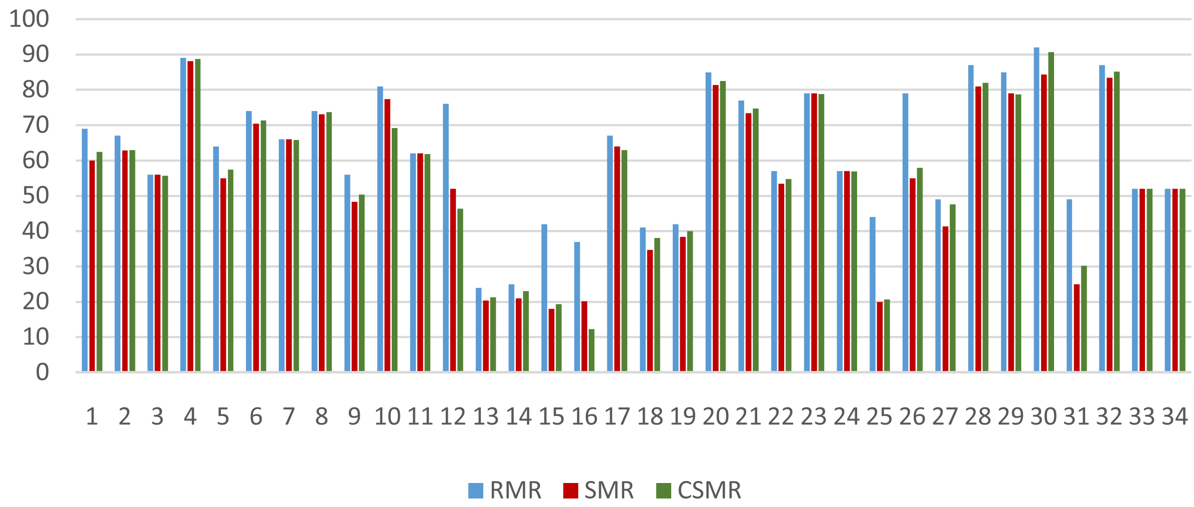

Fig.3. Comparison and Graphical Representation of RMR, SMR and CSMR

reclassification in categories IV and V. SMR classification catalogues 11.8 % of slopes in class IV and 11.8 % again in class V but 17.6 % of the slopes fall into unstable category (class IV) and 5.9 % in a completely unstable category (class V) as per CSMR classification. This is more in line with the field observation. This again reinforces the fact that SMR is conservative. The continuous assessment of cut-slope sections is more suitable for decisions regarding selecting slopes for deterministic slope stability analysis for design purpose and suggestion of remedial measures. It is also more suitable for incorporating into a spatial database.

CONCLUSIONS

Geomechanical rock mass classifications are a very convenient tool for quick assessment of rock quality and also helps in the characterization of rock masses.The stability of the slopes along the selected stretch of the Kodaikkanal - Palani traffic corridor was evaluated using three geomechanical classification systems- RMR, SMR and CSMR. Based on these classifications, the slopes were classified as completely stable, stable, partially stable, unstable and completely unstable. The study showed that only 9 % of the slopes were classified as vulnerable.RMR gives a reliable estimate of the rock mass except in case of highly disintegrated rock (RMR < 30).

SMR and CSMR classification indicated that nearly 24% of the slopes as vulnerable. Field verification and rock-fall history revealed that CMSR classification system yielded better results as failed slopes were identified more accurately. It is more appropriate for the identification of areas susceptible to local failure as CSMR is more sensitive to change in slope characteristics. This also makes implementation of the results on a spatial database. This system evaluates slopes as a continuous and hence, is useful for planning mitigation measures.

The SMR and CSMR analysis shows that adjustment factor F3 is the most critical factor in causing the instability of the slope. This factor is a measure the cut slope angle and discontinuity dip, meaning that the slopes are de-stabilized by road cutting activity. The condition worsens during periods of intense precipitation causing rock failures along the selected stretch.

The study area is a busy tourist destination round the year. The results of this study will be a vital input for developmental activities like construction of new roads or widening existing roads due to increase in traffic intensity. It will also help for feasibility studies, like route optimization for extension of existing hill roads.

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