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Slope mass rating of rock slopes of the Malekhu River, central Nepal Lesser Himalaya

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ABSTRACT

The Malekhu River is one of the major tributaries of the Trishuli Ganga River flowing from the south in Malekhu region, central Nepal. Riverbank slope stability is a topic of concern as rock mass condition and slope stability of riverbank slopes are important parameters for riverbank erodibility. Fourteen sites in the Malekhu River were selected for rock mass rating (RMR) and then slope mass rating (SMR) by using a graphic method. The potentially vulnerable sites were identified after conducting field study in different slopes. The results indicate that there occur modes of failures ranging from stable (good rock mass) to partially stable (normal rock mass) in all the study sites. The unstable (bad rock mass) and completely unstable (very bad rock mass) slopes are, however, distributed only in some slopes. The unstable slope of plane failure mode is Ka1, whereas the completely unstable slopes of plane failure mode are Rb2, Ml1 Slope 1 and Ml2. The unstable slope of toppling failure mode is Ml2. When wedge failure mode is considered, the slopes at Ti1 and Ka1 are unstable while the slopes at Kh1, Ka1, Ml1 Slope 1 are completely unstable. The rock slopes with unstable to completely unstable states are considered bad (SMR Class IV: 21–40) to very bad (SMR Class V: 0–20) rock mass with fair to poor rock mass rating, respectively. These bad to very bad rock mass slopes are vulnerable to slope movements and river erosion, and they require mitigative measures.

Key words: Rock mass rating, slope mass rating, Malekhu River, Lesser Himalaya

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INTRODUCTION

Riverbank slopes are vulnerable to erosion and lateral widening due to the action of river currents. The riverbank erosion hazard is controlled by several factors; bank composition (rock/soil) and structure, vegetation, surface protection, near bank stress condition, stability condition (shifting or incising) of the river and anthropogenic disturbance (Rosgen, 2001; Shrestha and Tamrakar, 2007a and 2007b; Maharjan and Tamrakar, 2010; Shrestha and Tamrakar, 2011). In the case of riverbank slope composed of rocks, the geomechanics properties of rocks are the crucial components which contribute for the input parameter of bank erosion hazard. Such components may be evaluated using the geomechanics classification of rock slopes.

Rock mass rating (RMR) was introduced and developed by Bieniawski (1973, 1976 and 1989). Geomechanics classification is a rock mass classification system of assigning a numeric rating to the quality and likely performance of a rock mass, based on easily measurable parameters (Goodman, 1989). RMR has become widely used geomechanics classification for tunnels and slopes to characterize rock mass for their behavior and stability. In 1985, Romana proposed a concept to RMR introducing some adjustment factors to basic RMR value to characterize the slope mass. This rating system, known as slope mass rating (SMR) after Romana (1985), was later endorsed by Bieniawski (1989). There are many other classifications; Slope rock mass rating (SRMR, Robertson, 1988), mining rock mass rating (MRMR, Laubscher, 1990), Chinese slope mass rating (CRMR, Chen, 1995), modified rock mass rating (M-RMR, Ünal, 1996), slope stability probability classification (SSPC, Hack et al., 2003), continuous rock mass rating (Sen and Sadagah, 2003), continuous slope mass rating (Tomás et al., 2007) and an alternative rock mass classification system (ARMCS, Pantelidis, 2010).

All these classifications are field based and require extensive determination of parameters. Among the geomechanical classification, RMR and SMR had got wide acceptance though the parameters in RMR (Bieniawski, 1989) and the adjustment factors in SMR of Romana (1985) are discrete and are decision based. RMR is independent of SMR, but is a major component for SMR calculation. The continuous slope mass rating of Tomás et al. (2007) is somewhat less decision based and allows unique value to each adjustment factors, and resulting into accurate value of final SMR (Tomás et al., 2007). Tomás et al. (2012) generated graphic method of determining the adjustment factors for SMR. This method allows for consideration of discontinuities which are potential for different failure modes, and reduces unnecessary computation of all those which do not have bearing on failure modes.

This paper aims to obtain status of slope stability condition of the Malekhu Riverbank rock slopes using SMR system after Romana (1985). For this the graphic method after Tomás et al. (2012) was adopted to determine the adjustment factors for deducing SMR for various rock slopes of the Malekhu River (Fig. 1). The study area is located at about 70 km west from Kathmandu. The Malekhu River flows from the south to the North across the Lesser Himalayan rocks to contribute to the Trishuli Ganga River at Malekhu.

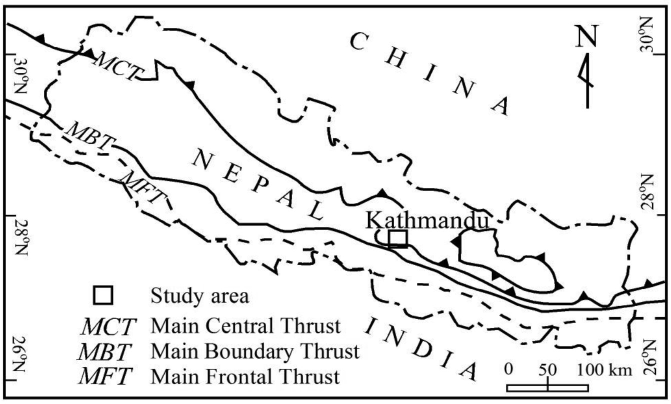


Fig. 1: Location of the study area.

GEOLOGICAL SETTING

The Lesser Himalaya is divisible into the Kathmandu Complex and the Nawakot Complex (Stöcklin and Bhattarai, 1977; Stöcklin, 1981). The Nawakot Complex exclusively made up of low grade metasedimentary rocks, and the Kathmandu Complex of higher grade rocks, which are separated by the Mahabharat Thrust (Stöcklin, 1980) (Fig. 2). The Nawakot complex is categorized into the Lower and the Upper Nawakot Groups. The Kathmandu Complex is subdivided into the Bhimphedi Group and the Phulchoki Group. The study area includes mainly the Upper Nawakot Group, the Bhimphedi Group and the Tistung Formation of the Phulchoki Group. The Upper Nawakot Group comprises the Benighat Slate, Malekhu Limestone and the Robang Formation. The Bhimphedi Group comprises: Raduwa Formation, Bhaisedobhan Marble, Kalitar Formation, Chisapani Quartzite, Kulekhani Formation and the Markhu Formation in ascending order from north to south (Fig. 2).

METHODS

The slope mass rating (SMR) is obtained by determining four factorial adjustment factors depending on the relative orientation of joints and slope and another adjustment factor depending on the method of excavation. SMR after Romana (1985) is defined as follows:

$$SMR = RMR_b + (F_1 \cdot F_2 \cdot F_3) + F_4$$

where,

RMR_b is the basic RMR index calculated from Bieniawski's (1989) RMR parameters to rock mass classification (Table 1). Five basic parameters as UCS, RQD, spacing of discontinuities, condition of discontinuity, and groundwater condition were determined from field observation for each site of rock mass sample to obtain the basic RMR value. The UCS was obtained from field estimation using a geological hammer and a pocket knife after Hoek and Brown (1997). The weathering grade of discontinuity surfaces was also determined using the same geological tools, in addition to appearance of colour and decomposition of the surfaces (after GSL 1977; Hencher and Martin 1982). RQD was obtained using the relation of Palmström (2005): RQD = (110-2.5Jv), where Jv is a joint volume determined for the rock mass. The remaining parameters of RMR were determined from the field observation and measurement. The Jv was determined using the following relation after Palmsröm (1974; 1982):

where, S1, S2, S3 are the average spacing for each of the

$$Jv = \frac{1}{S1} + \frac{1}{S2} + \frac{1}{S3} + ... + \frac{1}{Sn} + \frac{Nr}{5\sqrt{A}}$$

joint sets, Nr = number of random joints in actual location, and A = area in per cubic meter where random joints are counted.

F_1 depends on parallelism between dip direction of discontinuity (or trend of the line of intersection in the case of wedge failure) and slope dip direction (Table 2). According to Romana (1985) its range is from 1 to 0.15 and F_1 is defined as:

$$F_1 = (1\text{-Sin } A)^2$$

where, A = $|\alpha_j - \alpha_s|$, angle between discontinuity dip direction and slope face direction for plane failure; = $|\alpha_i - \alpha_s|$, angle between direction of line of intersection and slope face direction for wedge failure; = $|\alpha_j - \alpha_s - 180|$ for toppling failure.

F_2 depends on the discontinuity dip amount in the case of plane failure and the plunge of line of intersection in the case of wedge failure. For toppling failure F_2 is taken as 1.00. This parameter is related to the probability of discontinuity shear strength (Romana, 1993). In discrete method, F_2 is given by the relationship:

$$F_2 = \tan^2 B$$

where, B = $|\beta_j|$ for plane failure and $|\beta_i|$ for wedge failure. F_2 ranges from 0.15 to 1.00 (Table 2).

F_3 depends on the relationship between slope, β_s and discontinuity dips, β_j for planar or toppling failure, and the plunge of line of intersection, β_i in wedge failure. F_4 is the adjustment factor for the method of excavation, which has been fixed as +15 for natural slopes, +10 for pre-splitting, +8 for smooth blasting, 0 for normal blasting or mechanical excavation, and -8 for deficient blasting (Romana et al., 1993).

The adjustment factors F_1, F_2 and F_3 are multiplied and the product is added to F_4 and finally to RMR_b to obtain SMR. This method of assigning the rating for each parameter

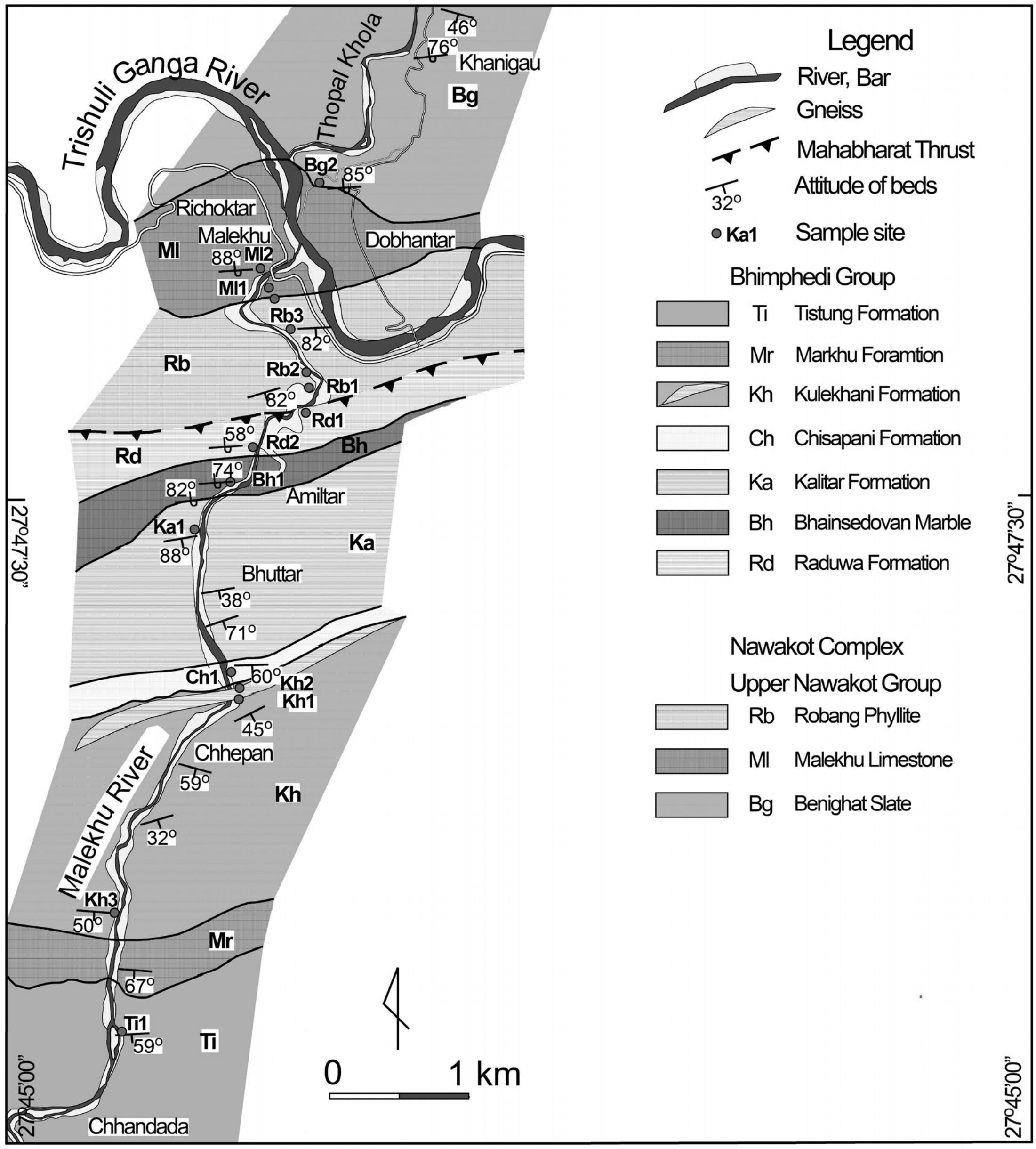


Fig. 2 Geological map of the Malekhu area along the river sections in N-S direction.

from the table is the discrete method. The graphic method of determining these parameters using stereographic projections is superior as large number of discontinuity data can be used to define the mean discontinuity planes and the potential wedges can be selected to directly read the rating factors from the template defined by Tomás et al. (2012) as shown in Figs. 3 and 4.

In the graphic method of obtaining adjustment factors, the Ψ value (which is a product of F_1 and F_2), and the F_3 factor are determined separately using separate templates of stereographic projections for three different modes of failure (Fig. 3). The Ψ value templates of three separate modes of failure (Fig. 3) can be used for every slope, whereas the F_3 parameter is read from the F_3 template constructed for the particular slope (Fig. 4), and can not be used for the other slopes. The stability classes based on RMR are shown in Table 3 (after Romana, 1985). SMR is categorized into five classes: I = completely stable, II = stable, III = partially stable, IV = unstable, and V = completely unstable.

RESULTS

The samples against lithology, slope and discontinuities are listed in Table 4. All the discontinuity sets were identified not only from the field but also by extensive plotting of poles of discontinuities in stereonet to finally derive the planes from the pole maxima. Most of the sample sites consist of at least three sets of discontinuities. In some cases, four to five sets of discontinuities are present (Table 4).

Table 1: Rock Mass Rating parameters and rating after Bieniawski (1989)

Parameters		Ranges of values						
UCS (Mpa)	Value	>250	100 to 250	50 to 100	25 to 5	5 to 25	1 to 5	<1
	Rating	15	12	7	4	2	1	0
RQD	Value	90 to 100	75 to 90	50 to 75	25 to 50		<25	
	Rating	20	17	13	8		3	
Spacing of discontinuity	Value	>2m	0.6 to 2m	200 to 600mm	60 to 200mm		<60mm	
	Rating	20	15	10	8		5	
Condition of discontinuity	Value	Very rough surface; no separation; not continuous; unweathered walls	Slightly rough; separation <1mm; slightly weathered walls	Slightly rough surface; separation < 1mm; highly weathered walls	Slickensided surface or gouge < 5mm or separation 1-5mm; continuous		Soft gouge > 5mm or separation > 5mm; continuous	
	Rating	30	25	7	4		5	
Groundwater in joint	Value	Completely dry	Damp	Wet	Dripping		Flowing	
	Rating	15	10	7	4		0	

Table 2: Adjustment rating for joints and excavation of slope after Romana (1985) and Tomas et al. (2011)

Adjustment rating for joints							
Case			Very favourable	Favourable	Fair	Unfavourable	Very unfavourable
P	A	$\|\alpha_j-\alpha_s\|$	>30°	30° to 20°	20° to 10°	10° to 5°	< 5°
T		$\|(\alpha_i-\alpha_s)-180°\|$					
W		$\|\alpha_j-\alpha_s\|$					
P/T/W	F1		0.15	0.40	0.70	0.85	1.00
P	B	$\|\beta_j\|$	<20°	20° to 30°	30° to 35°	35° to 45°	>45°
W		$\|\beta_i\|$					
P/W	F2		0.15	0.40	0.70	0.85	1.00
T			1.00	1.00	1.00	1.00	1.00
P	C	$\beta_j-\beta_s$	>10°	10° to 0°	0°	0° to (-10°)	<-10°
W		$\beta_i-\beta_s$					
T		$\beta_j+\beta_s$	<110°	110° to 120°	>120°	_	_
P/W/T	F3		0	-6	-25	-50	-60
Adjustment rating for method of excavation of slopes							
			Natural slope	Presplitting	Smooth blasting	Blasting or mechanical	Deficient blasting
	F4		15	10	8	0	-8

P = planar failure; T = toppling failure; W = wedge failure

β_j= joint dip β_s= slope dip β_i = angle of plunge of the intersection line of two sets of discontinuities;

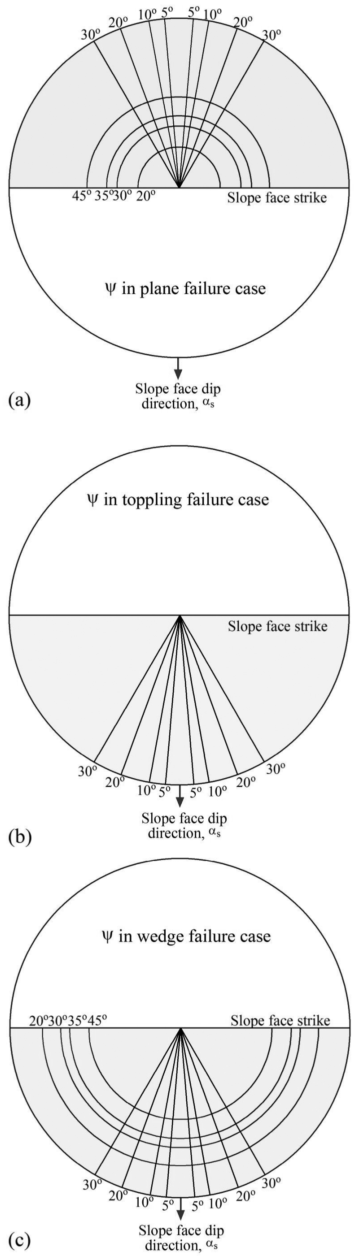
α_j= joint dip direction; α_s= slope dip direction; α_i = dip direction of the intersection line of two sets of discontinuities

Basic RMR

Based on RMR classification, the rock masses of Ti1, Kh3, Ch1, Bh1, Rd2, Rd1, Rb2, Rb1, Ml1 and Ml2 are fair rocks in which RMR ranges from 41 to 60. The rock masses of Kh1 and Rb3 are good rocks (RMR 61–80; Table 5). The rock mass of Kh2 which has RMR of 82 is very good rock (RMR 81–100). The rock mass of Ka1 having RMR of 39 lies in poor rock category (RMR 21–40).

SMR of Riverbank Slopes

The Malekhu Riverbank slopes have steep (36°–45°) to very steep (>45°) dip angle, after slope categories of Deoja et al. (1991), with well-developed system of discontinuities. Slope mass rating (SMR) for individual rock mass sample site was performed using the basic RMR data which was adjusted for the number of joint related factors such as F1, F2 and F3, and the method of excavation factor F4. The product of F1 and F2, which is designated as Ψ, and the F3 factor were obtained individually using the stereographic template (Figs. 3 and 4) as designed by Tomás et al. (2012). One example of stereographic plot of discontinuity data to obtain Ψ factor and F3 factor is shown in Fig. 5, and the results for all fourteen rock mass sample sites have been listed in Table 6.



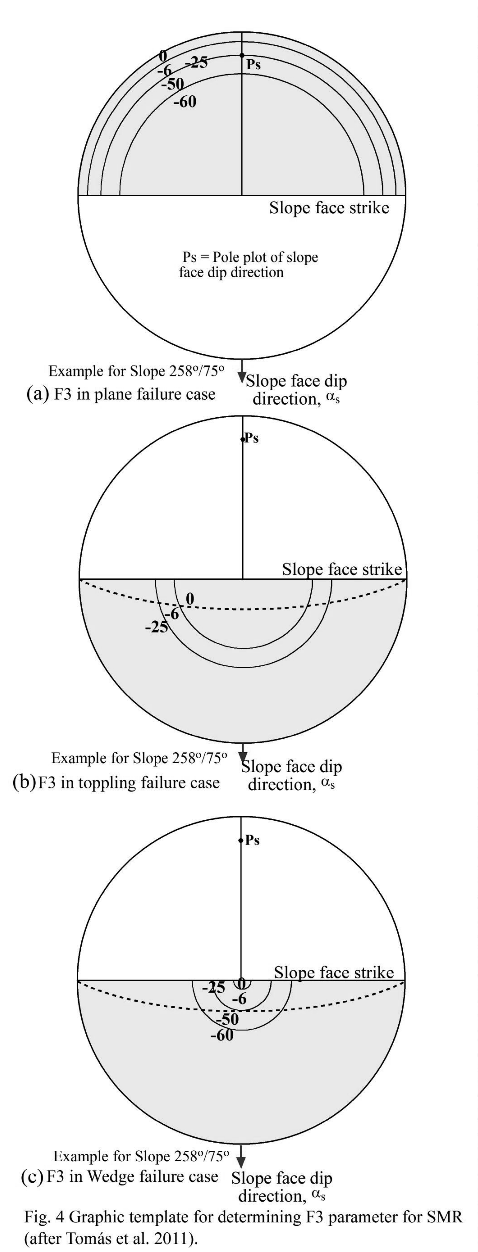


Fig. 3 Graphic template for determining Ψ parameter for SMR (after Tomás et al., 2011) : (a) Plane failure case, (b) Toppling failure case, and (c) Wedge failure case.

Fig. 4 Graphic template for determining F3 parameter for SMR (after Tomás et al. 2011) : (a) Plane failure case, (b) Toppling failure case, and (c) Wedge failure case.

The listing in Table 6 includes all those probable failure modes, but depending on the basic RMR and the angular relationships between discontinuity and slope face, the SMR obtained for each differ and the final stability categories come to range from completely unstable to stable.

The slope of the Ti1 contains four major joint sets, which are considered partially stable (class III) in terms of plane failure and toppling failure causes, but are considered partially stable and unstable (class IV) in the wedge failure case. Therefore, there exists on unstable wedge produced by intersection of J1 and J2.

In the slope of the Kh3, rock mass is stable in cases of plane and toppling failures and are classified as stable rock mass (class II). There are four intersections, for which SMR values ranging from 43 (partially stable) to 63 (stable). In the Kh2 slope 1, there are three planes showing partially stable to stable states. The slope is stable in toppling failure case. In wedge failure case, all the lines of intersections are partially

Table 3: Stability classes based on SMR (Romana, 1985)

Classes	V	IV	III	II	I
SMR	0-20	21-40	41-60	61-80	81-100
Rock mass Description	Very bad	Bad	Normal	Good	Very good
Stability	Completely unstable	Unstable	Partially stable	Stable	Completely stable
Failure	Big planar or soil-like or circular	Planar or big wedge failure	Planar along some joints or many wedge failure	Some block failure	None

stable. But in the slope of Kh2, planes are almost stable in all failure cases except 1 plane and 1 wedge which lie in class III (partially stable) although it has RMR value 82. The slope of Kh1 can be classified as stable as it has SMR of 62 in plane failure case and 63 in topple failure case. Slope may be classified as completely unstable (class V) for wedge J1-J2 as it has SMR equals to 13 only.

The slope of Ch1 is partially stable in all three cases. In the slope of Ka1, slopes are unstable to completely unstable in wedge failure case, stable to unstable in plane failure case and partially stable in topple failure case. Considering the slope of Bh1, plane and wedge both are stable than the topple case that is categorized into partially stable (class III) to stable (class II).

The slopes Rd1 and Rd2 have stable to partially stable slopes in terms of plane failure and toppling failure cases. But in Rd1, slope is stable in terms of wedge failure but there is partially stable condition in Rd2 although both the locations have fair rock mass.

The slope Rb1 has five major joints planes which contain three planes of partially stable to stable conditions of plane failure, and stable in terms of toppling failure. There are six wedges which are classified as III (partially stable) due to fair rock mass. In the case of Rb2, one plane is completely unstable with SMR value only 3, whereas in Rb3 it is stable in plane cases. But in both Rb2 and Rb3, slopes are stable in wedge failure case and partially stable in toppling failure case.

The Slope 1 at Ml1 has three planes with SMR values 3 (completely unstable), 62 (stable) and 63 (stable). The slope is stable in terms of toppling failure, and is completely unstable (SMR = 12) for intersection formed by Joint 1 and Joint 3, though other two intersections lie in stable category. The Slope 2 at Ml1 also has two planes of partially stable and stable states. There are one stable and one partially stable states of toppling failure cases, and one stable and two partially stable lines of intersections. The location Ml2 displays on completely unstable plane (SMR =12) and one stable plane (SMR = 63). The slope also contains one partially stable plane and one unstable plane in toppling failure case. The slope Ml2 contains all the three partially stable (SMR = 42–59) lines of intersections produced by discontinuities.

DISCUSSIONS

In plane failure case, only stable (II) conditions reflected by discontinuities are found in Kh3, Kh1, Bh1 and Rb3. Partially stable (III) to stable conditions are met in Kh2 (both Slopes 1 and 2), Ka1, Rd2, Rd1, Rb1 and Ml1 (both Slopes 1 and 2). But discontinuities in Ti1 and Ch1 have all partially stable condition of plane failure mode. Completely unstable to unstable slopes in terms of plane failure are found in Ml1 slope 1, Ml2, and Rb2.

Considering the toppling failure case, partially stable conditions (SMR between 41 and 60) are found in Ch1, Ka1, Bh1, Rd1, Rb1, Ml1 (both slope 1 and slope 2) and Ml2. The rock mass of Ml2 is unstable due to discontinuity J1 (Table 6), while the rest of the other locations show good rock masses and discontinuities with stable toppling mode of failure (in these cases SMR ranging from 61–63).

The wedge failure mode is the most pronounced of all the failure modes as intersection of discontinuities produces several wedges which are probable to failure. Completely unstable (SMR <20) slopes due to daylight of lines of intersection are met in Kh1, Ka1, and Ml1 (Slope 1). Unstable (SMR between 21 and 40) slopes are found in Ti1, Ka1, and Ml1 (Slopes 1 and 2). In other sites wedge failure cases are partially stable to stable. Bh1 (SMR 61) and Rd1 (SMR 62–63) constitute discontinuities which intersect to produce wedges of stable condition.

SMR values obtained are independent of RMR basic parameters. Though it seems to be positively related, the correlations between either individual SMR for each mode of failure or the total SMR values and RMR are very weak (Fig. 6). Hence, it can be said that there is no tendency of increase in SMR due to the increase in RMR basic. Therefore, there is more to do with attitudes of discontinuities and their relation with slope face attitude to enhance or worsen the SMR values.

The plane failure mode is completely unstable in Rb2, Ml1 and Ml2. In all cases, rock masses are fair (RMR within 41–60), but the low ratings of Ψ and F3 factors contribute in reducing the SMR.

Table 4: Sample, lithology, slope and discontinuity

Sample	Formation	Lithology	Slope 1	Slope 2	Joint set J1	J2	J3	J4	J5
Ti1	Tistung	Metasandstone	244°/80°		180°/62°	275°/71°	125°/70°	22°/52°	–
Kh3	Kulekhani	Biotite schist and quartzose schist	130°/30°		24°/49°	92°/77°	187°/37°	214°/89°	–
Kh2	Kulekhani	Massive augen gneiss	160°/60°	260°/40°	163°/63°	61°/55°	247°/47°	222°/72°	–
Kh1	Kulekhani	Biotite schist with bands of migmatite	205°/55°		162°/59°	238°/59°	21°/24°	–	–
Ch1	Chisapani Quartzite	Quartzite with thin schist	240°/65°		170°/59°	52°/63°	248°/71°	300°/22°	
Ka1	Kalitar	Biotite schist	92°/75°		177°/77°	36°/55°	86°/66°	353°/88°	224°/65°
Bh1	Bhaisedovan Marble	Marble with schistose partings	150°/40°		345°/46°	127°/46°	253°/72°	–	–
Rd2	Raduwa	Schist with quartzose bands	78°/50°		238°/45°	120°/50°	84°/71°	344°/55°	–
Rd1	Raduwa	Garnetiferous schist	272°/30°		165°/43°	273°/20°	102°/83°	28°/88°	–
Rb3	Robang	Quartzite with sericite partings	182°/55°		174°/79°	274°/53°	79°/59°	352°/88°	–
Rb2	Robang	Greenish grey schist	75°/85°		180°/4°	77°/69°	299°/86°	–	–
Rb1	Robang	Quartzite	340°/48°		166°/80°	309°/16°	82°/59°	41°/25°	267°/67°
Ml1	Malekhu Limestone	Laminated, fine dark grey dolomite	290°/72°	258°/75°	284°/59°	237°/17°	188°/82°	2°/88°	–
Ml2	Malekhu Limestone	Laminated, fine dark grey dolomite	252°/70°		73°/49°	257°/58°	161°/85°	340°/87°	–

Table 5: Results of rock mass rating

Sample		UCS	RQD	Discontinuity spacing	Condition of discontinuity: [b]Persistency	[c]Aperture	[d]Roughness	[e]Filling	[f]Weathering	Groundwater condition	RMR	Remarks
Ti1	Observation	strong	Good	wide to mod.	H to VH	VW	R	S>5mm	S	wet		
	Rating	7	13	11	1	0	5	0	5	7	48	fair
Kh3	Observation	VS	Fair	mod.to close	L to VH	VT to T	SR to S	N to S<5mm	S	Damp		
	Rating	12	13	9	1	5	1	3	5	10	59	fair
Kh2	Observation	ES	Excellent	v. wide	H to VH	VW	VR to R	S>5mm	S	c. dry		
	Rating	15	20	20	1	0	6	0	5	15	82	v. good
Kh1	Observation	strong	Excellent	mod.-v. close	L to H	VT to VW	R to SR	N to S>5mm	S	Damp		
	Rating	7	20	8	2	4	4	4	5	10	64	good
Ch1	Observation	strong	Fair	wide to close	L to VH	VW	R to SR	S>5mm	S	C. dry		
	Rating	7	13	11	2	0	5	0	5	15	58	fair
Ka1	Observation	MS	Fair	mod. to close	M to VH	VW	VR to R	S>5mm	M	dripping		
	Rating	4	13	8	1	0	6	0	3	4	39	poor
Bh1	Observation	strong	Fair	mod. to close	L to VH	VW	R to SR	S >5mm	S to M	Damp		
	Rating	7	8	9	3	0	4	0	3	10	44	fair
Rd2	Observation	strong	Fair	moderate	VL to VH	VW	R to SR	S>5mm	M	Damp		
	Rating	7	13	10	3	0	4	0	3	10	50	fair
Rd1	Observation	strong	Excellent	wide to mod.	H to VH	VW	VR to SR	S>5mm	S	Damp		
	Rating	7	20	12	1	0	5	0	5	10	60	fair
Rb3	Observation	VS	Fair	wide to close	VL to VH	MO to O	R to SR	S<5mm	S	Damp		
	Rating	12	17	12	1	3	4	2	5	10	66	good
Rb2	Observation	S	Fair	mod. to close	H to VH	VW	R to SR	S<or>5mm	S	Damp		
	Rating	7	8	9	1	0	4	1	5	10	45	fair
Rb1	Observation	ES	V. poor	mod. to close	H to VH	VT to VW	R to Sl	N to S>5mm	S	C. dry		
	Rating	15	3	9	1	4	1	4	5	15	57	fair
Ml1	Observation	VS to MS	poor	close	H	MO to VW	S to R	N to S>5mm	S	C. dry		
	Rating	12	8	8	2	2	1	4	5	15	57	fair
Ml2	Observation	VS to MS	Fair	close-v.close	M to VH	T to VW	R to S	N to S>5mm	S	Damp		
	Rating	12	13	9	1	2	3	2	5	10	57	fair

R1= strength in intact rock material; R2= Rock Quality Desingnation; R3= spacing of discontinuiteis; R4= condition of discontinuities; R5= ground water

RMR value: <21 very poor rock; 21–40 poor rock; 41–60 fair rock; 61-80 good rock; 81–100 very good rock

[a] R1: MS = moderately strong; S = strong; VS = very strong; ES = extremely strong

[b] Persistency: VL=very low; L=low; M=medium; H=high, VH=very high

[c] Aperture: O=open; MO=moderately open; W=wide; VW=very wide; T=tight; VT=very tight

[d] Roughness: S=smooth; SR=slightly rought; R=rough; vR=very rought; Sl=slickenside;

[e] Filling: H=hard; S=soft; N=none

[f] Weathering: S=slight; M=moderate;

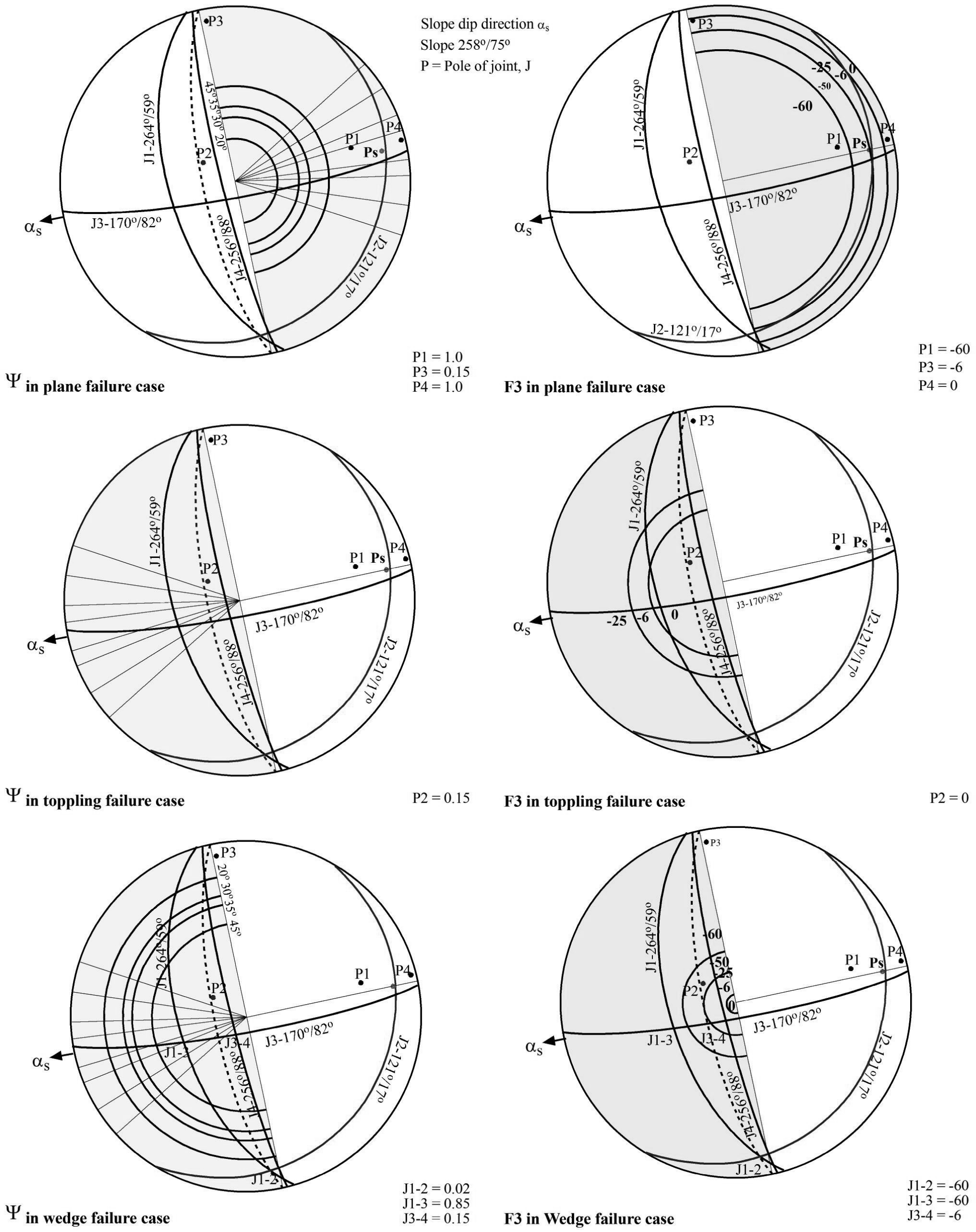


Fig. 5 Stereographic projection of discontinuity data of Ml1, and using of templates for defining the adjustment factors, Ψ and F3.

High possibility of toppling is seen in rock slopes of Ml2 where the condition rock mass is unstable due to fair rock mass (RMR = 57) and very low to moderately low rating factors of Ψ and F3, respectively. Partially stable slopes of Ch1, Ka1, Bh1, Rd1, Rb1, Ml1 and Ml2 are in some cases contributed by fairly high RMR and moderately low adjustment factors (Ψ and F3), and in some cases fairly low RMR but moderately higher adjustment factors.

Completely unstable to unstable slopes in terms of wedge failure are Kh1, Ka1 and Ml1. The slope in the Ti1 is unstable. In these slopes though the slopes have moderately high RMR values, the adjustment parameters are quite low, and contribute in lowering the SMR values.

Table 6: Results of slope mass rating

Sample	RMR_b	Joint sets	Failure mode	Joint attitude α_j/β_j	Slope attitude α_s/β_s	Ψ (=F1xF2)	F3	F1xF2xF3	F4	SMR	Class	Rock mass	Stability
Ti1	48	J1	P	180°/62°	244°/80°	0.15	-60	-9.0	15	54	III	Normal	Partially stable
		J2	P	275°/71°	244°/80°	0.4	-50	-20.0	15	43	III	Normal	Partially stable
		J3	T	125°/70°	244°/80°	0.15	-25	-3.8	15	59	III	Normal	Partially stable
		J4	T	22°/52°	244°/80°	0.15	-25	-3.8	15	59	III	Normal	Partially stable
		J1-2	W	216°/57°	244°/80°	0.4	-60	-24.0	15	39	IV	Bad	Unstable
		J1-J3	W	173°/61°	244°/80°	0.15	-60	-9.0	15	54	III	Normal	Partially stable
		J2-J3	W	199°/36°	244°/80°	0.13	-60	-7.8	15	55	III	Normal	Partially stable
Kh3	59	J3	P	187°/37°	130°/30°	0.15	0	0	15	63	II	Good	Stable
		J1	P	24°/49°	130°/30°	0.13	-6	-0.78	15	62	II	Good	Stable
		J2	T	92°/77°	130°/30°	0.15	0	0	15	63	II	Good	Stable
		J4	T	214°/89°	130°/30°	0.15	-6	-0.9	15	62	II	Good	Stable
		J1-J2	W	112°/12°	130°/30°	0.11	-60	-6.6	15	56	III	Normal	Partially stable
		J1-J3	W	174°/36°	130°/30°	0.13	-6	-0.78	15	62	II	Good	Stable
		J1-J4	W	135°/25°	130°/30°	0.4	-50	-20	15	43	III	Normal	Partially stable
		J3-J4	W	137°/70°	130°/30°	0.7	0	0	15	63	II	Good	Stable
Kh2 Slope 1	82	J1	P	163°/63°	160°/60°	1	-6	-6	15	57	III	Normal	Partially stable
		J3	P	247°/47°	160°/60°	0.15	-60	-9	15	54	III	Normal	Partially stable
		J4	P	222°/72°	160°/60°	0.15	0	0	15	63	II	Good	Stable
		J2	T	61°/55°	160°/60°	0.15	-6	-0.9	15	62	II	Good	Stable
		J1-J2	W	106°/45°	160°/60°	0.15	-60	-9	15	54	III	Normal	Partially stable
		J1-J3	W	222°/45°	160°/60°	0.13	-60	-7.8	15	55	III	Normal	Partially stable
		J1-J4	W	172°/63°	160°/60°	0.7	-6	-4.2	15	59	III	Normal	Partially stable
		J2-J4	W	156°/19°	160°/60°	0.06	-60	-3.6	15	59	III	Normal	Partially stable
Kh2 Slope 2		J3	P	247°/47°	260°/40°	0.7	-6	-4.2	15	59	III	Normal	Partially stable
		J4	P	222°/72°	260°/40°	0.15	0	0	15	63	II	Good	Stable
		J1	T	163°/63°	260°/40°	0.15	0	0	15	63	II	Good	Stable
		J2	T	61°/55°	260°/40°	0.7	0	0	15	63	II	Good	Stable
		J1-J3	W	222°/45°	260°/40°	0.13	-6	-0.78	15	62	II	Good	Stable
		J1-J4	W	172°/63°	260°/40°	0.15	0	0	15	63	II	Good	Stable
		J3-J4	W	300°/33°	260°/40°	0.11	-50	-5.5	15	58	III	Normal	Partially stable
		J2-J3	W	334°/3°	260°/40°	0.02	-60	-1.2	15	62	II	Good	Stable
Kh1	47	J1	P	162°/59°	205°/55°	0.15	-6	-0.9	15	62	II	Good	Stable
		J2	P	238°/59°	205°/55°	0.15	-6	-0.9	15	62	II	Good	Stable
		J3	T	21°/24°	205°/55°	1.00	0	0	15	63	II	Good	Stable
		J1-2	W	200°/52°	205°/55°	1.00	-50	-50	15	13	V	V. bad	Completely unstal
Ch1	58	J1	P	170°/59°	240°/65°	0.15	-50	-7.5	15	56	III	Normal	Partially stable
		J4	P	300°/22°	240°/65°	0.06	-60	-3.6	15	59	III	Normal	Partially stable
		J2	T	52°/63°	240°/65°	0.85	-25	-21.25	15	42	III	Normal	Partially stable
		J3	T	248°/71°	240°/65°	0.15	-25	-3.75	15	59	III	Normal	Partially stable
		J1-J3	W	259°/3°	240°/65°	0.11	-60	-6.6	15	56	III	Normal	Partially stable
		J1-J4	W	251°/14°	240°/65°	0.11	-60	-6.6	15	56	III	Normal	Partially stable
		J3-J4	W	265°/18°	240°/65°	0.06	-60	-3.6	15	59	III	Normal	Partially stable
Ka1	39	J1	P	177°/77°	92°/75°	0.15	-6	-0.9	15	62	II	Good	Stable
		J2	P	36°/55°	92°/75°	0.15	-60	-9	15	54	III	Normal	Partially stable
		J3	P	86°/66°	92°/75°	0.85	-50	-42.5	15	21	IV	Bad	Unstable
		J4	T	353°/88°	92°/75°	0.15	-25	-3.75	15	59	III	Normal	Partially stable
		J5	T	224°/65°	92°/75°	0.15	-25	-3.75	15	59	III	Normal	Partially stable
		J1-J2	W	96°/35°	92°/75°	0.85	-60	-51	15	12	V	V. bad	Completely unstal
		J1-J3	W	112°/63°	92°/75°	0.4	-60	-24	15	39	IV	Bad	Unstable
		J2-J3	W	37°/55°	92°/75°	0.15	-60	-9	15	54	III	Normal	Partially stable
		J2-J4	W	81°/45°	92°/75°	0.7	-60	-42	15	21	IV	Bad	Unstable
		J30J4	W	81°/67°	92°/75°	0.85	-50	-42.5	15	21	IV	Bad	Unstable
		J3-J5	W	155°/38°	92°/75°	0.13	-60	-7.8	15	55	III	Normal	Partially stable

Bh1	44	J2	P	127°/46°	150°/40°	0.4	-6	-2.4	15	61	II	Good	Stable
		J1	T	345°/46°	150°/40°	0.7	-6	-4.2	15	59	III	Normal	Partially stable
		J3	T	253°/72°	150°/40°	0.4	-6	-2.4	15	61	II	Good	Stable
		J2-J3	W	68°/27°	150°/40°	0.03	-60	-1.8	15	61	II	Good	Stable
Rd2	50	J2	P	120°/50°	78°/50°	0.15	-25	-3.75	15	59	III	Normal	Partially stable
		J3	P	84°/71°	78°/50°	0.85	0	0	15	63	II	Good	Stable
		J1	T	238°/45°	78°/50°	0.4	0	0	15	63	II	Good	Stable
		J4	T	344°/55°	78°/50°	0.15	0	0	15	63	II	Good	Stable
		J2-J3	W	154°/44°	78°/50°	0.15	-50	-7.5	15	56	III	Normal	Partially stable
		J2-J4	W	55°/26°	78°/50°	0.16	-60	-9.6	15	53	III	Normal	Partially stable
		J3-J4	W	19°/50°	78°/50°	0.15	-6	-0.9	15	62	II	Good	Stable
Rd1	60	J2	P	273°/20°	272°/30°	0.15	-25	-3.75	15	59	III	Normal	Partially stable
		J4	P	28°/88°	272°/30°	0.85	0	0	15	63	II	Good	Stable
		J1	T	165°/43°	272°/30°	0.15	0	0	15	63	II	Good	Stable
		J3	T	102°/83°	272°/30°	0.7	-6	-4.2	15	59	III	Normal	Partially stable
		J1-J2	W	237°/16°	272°/30°	0.02	-60	-1.2	15	62	II	Good	Stable
		J1-J3	W	185°/41°	272°/30°	0.13	0	0	15	63	II	Good	Stable
		J1-J4	W	192°/40°	272°/30°	0.13	-6	-0.78	15	62	II	Good	Stable
		J2-J3	W	190°/6°	272°/30°	0.02	-60	-1.2	15	62	II	Good	Stable
Rb3	66	J1	P	174°/79°	182°/55°	0.85	0	0	15	63	II	Good	Stable
		J2	T	274°/53°	182°/55°	0.15	0	0	15	63	II	Good	Stable
		J3	T	79°/59°	182°/55°	0.15	-6	-0.9	15	62	II	Good	Stable
		J4	T	352°/88°	182°/55°	0.7	-25	-17.5	15	46	III	Normal	Partially stable
		J1-J2	W	251°/50°	182°/55°	0.15	-50	-7.5	15	56	III	Normal	Partially stable
		J1-J4	W	263°/8°	182°/55°	0.02	-60	-1.2	15	62	II	Good	Stable
		J1-J3	W	103°/57°	182°/55°	0.15	-6	-0.9	15	62	II	Good	Stable
		J2-J4	W	265°/52°	182°/55°	0.15	-25	-3.75	15	59	III	Normal	Partially stable
Rb2	45	J2	P	77°/69°	75°/85°	1	-60	-60	15	3	V	V. bad	Completely unstable
		J1	T	180°/4°	75°/85°	0.15	0	0	15	63	II	Good	Stable
		J3	T	299°/86°	75°/85°	0.15	-25	-3.75	15	59	III	Normal	Partially stable
		J2-J3	W	24°/58°	75°/85°	0.15	-60	-9	15	54	III	Normal	Partially stable
Rb1	57	J2	P	309°/16°	340°/48°	0.02	-60	-1.2	15	62	II	Good	Stable
		J4	P	41°/25°	340°/48°	0.156	-60	-9.36	15	54	III	Normal	Partially stable
		J5	P	267°/67°	340°/48°	0.15	0	0	15	63	II	Good	Stable
		J1	T	166°/80°	340°/48°	0.85	-25	-21.25	15	42	III	Normal	Partially stable
		J3	T	82°/59°	340°/48°	0.15	0	0	15	63	II	Good	Stable
		J1-J2	W	255°/9°	340°/48°	0.02	-60	-1.2	15	62	II	Good	Stable
		J2-J3	W	358°/11°	340°/48°	0.11	-60	-6.6	15	56	III	Normal	Partially stable
		J2-J4	W	344°/14°	340°/48°	0.15	-60	-9	15	54	III	Normal	Partially stable
		J2-J5	W	352°/12°	340°/48°	0.11	-60	-6.6	15	56	III	Normal	Partially stable
		J3-J4	W	5°/20°	340°/48°	0.16	-60	-9.6	15	53	III	Normal	Partially stable
		J3-J5	W	355°/4°	340°/48°	0.11	-60	-6.6	15	56	III	Normal	Partially stable
		J4-J5	W	348°/16°	340°/48°	0.13	-60	-7.8	15	55	III	Normal	Partially stable
Ml1 Slope 1	57	J1	P	264°/59°	258°/75°	1.00	-60	-60	15	3	V	V. bad	Completely unstable
		J3	P	170°/82°	258°/75°	0.15	-6	-0.9	15	62	II	Good	Stable
		J4	P	256°/88°	258°/75°	1	0	0	15	63	II	Good	Stable
		J2	T	221°/17°	258°/75°	0.15	0	0	15	63	II	Good	Stable
		J1-J2	W	179°/9°	258°/75°	0.02	-60	-1.2	15	62	II	Good	Stable
		J1-J3	W	247°/58°	258°/75°	0.85	-60	-51	15	12	V	V. bad	Completely unstable
		J3-J4	W	210°/80°	258°/75°	0.15	-6	-0.9	15	62	II	Good	Stable
Ml1	57	J1	P	264°/59°	290°/72°	0.15	-60	-9	15	54	III	Normal	Partially stable
Slope 2		J4	P	256°/88°	290°/72°	0.15	0	0	15	63	II	Good	Stable
		J2	T	121°/17°	290°/72°	0.7	0	0	15	63	II	Good	Stable
		J3	T	170°/82°	290°/72°	0.15	-25	-3.75	15	59	III	Normal	Partially stable
		J1-J3	W	250°/55°	290°/72°	0.15	-60	-9	15	54	III	Normal	Partially stable
		J1-J4	W	270°/58°	290°/72°	0.15	-60	-0.9	15	62	II	Good	Stable
Ml2	57	J2	P	257°/58°	252°/70°	0.85	-6	-51	15	12	V	V. bad	Completely unstable
		J4	P	340°/87°	252°/70°	0.15	0	0	15	63	II	Good	Stable
		J1	T	73°/49°	252°/70°	1	-25	-25	15	38	IV	Bad	Unstable
		J3	T	161°/85°	252°/70°	0.15	-25	-3.75	15	59	III	Normal	Partially stable
		J2-J3	W	241°/57°	252°/70°	0.85	-25	-21.25	15	42	III	Normal	Partially stable
		J2-J4	W	257°/60°	252°/70°	0.85	-25	-21.25	15	42	III	Normal	Partially stable

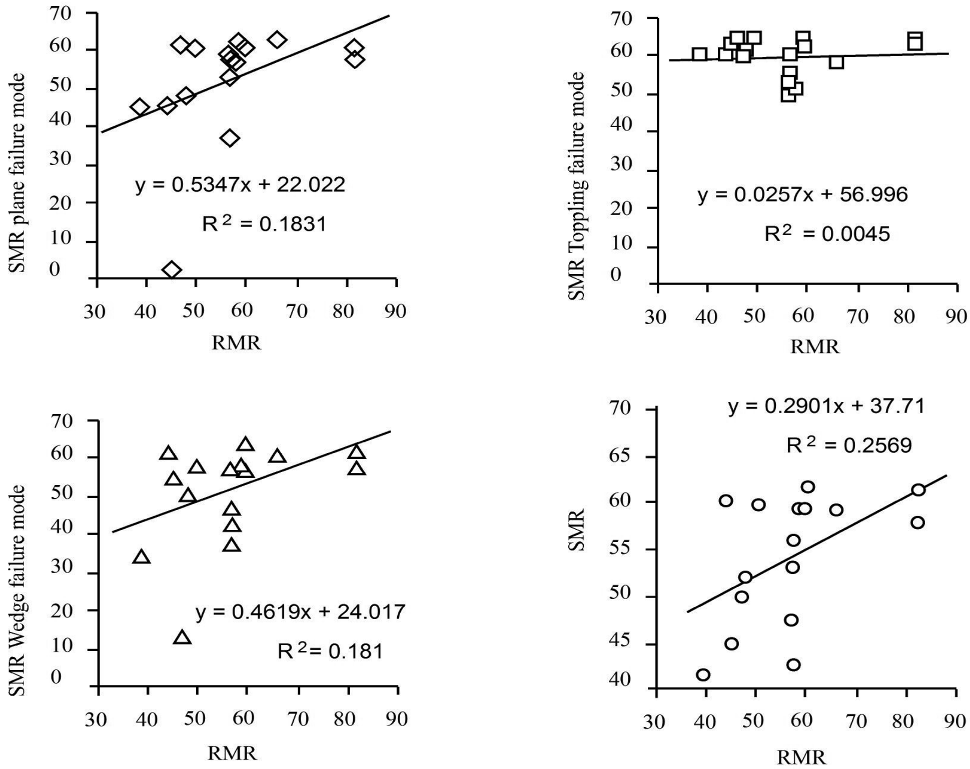


Fig. 6 Relationship between SMR and RMR obtained for the rock slopes of the Malekhu River area.

CONCLUSIONS

The fourteen riverbank rock slopes have been studied in the Malekhu River. The graphic method of determining adjustment factors is found to have advantage on sorting out of the daylight planes and lines of intersections, thereby reducing unnecessary consideration of every discontinuity for calculating the adjustment factors. SMR values indicate mainly plane and wedge types of failure modes and few toppling failures based on the joints and slope face configuration. Correlation between SMR and RMR is very weak. The results of analysis shows that possibility of all the failure types exists in all the sites and they vary from stable to completely unstable states. The following modes of failure are unstable (SMR Class IV) to completely unstable (SMR Class V) at various locations based on stability classes of SMR after Romana (1985):

(a) Plane failure case: unstable slope is Ka1, and completely unstable slopes are Rb2, Ml1 Slope 1 and Ml2.

(b) Toppling failure case: unstable slope is Ml2.

(c) Wedge failure case: unstable slopes are Ti1 and Ka1, whereas completely unstable slopes are Kh1, Ka1 and Ml1 Slope 1.

The rock slopes, where unstable to completely unstable states exist, are considered having bad (fair RMR) to very bad (poor RMR) rock mass conditions, respectively. These bad to very bad rock mass slopes are vulnerable to slope movement and riverbank erosion, and require mitigation measures to be implemented.

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