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Research Paper

Stability Analysis of the Natural Slopes of the Poponguine Cliff (Senegal) using the SMR and CSMR Methods

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ABSTRACT

The aim of this study is to analyse the stability of the Poponguine rock cliff using the SMR methods. The SMR and CSMR methods are based on the RMR geomechanical classification and on the identification of potential kinematic failures using stereographic projection. Three stations, designated S1, S2 and S3, were defined in order to apply the SMR methods to the Poponguine cliff. The RMR values at the three stations indicate an average rock mass, with respective RMR ratings of 48 (S1), 50 (S2) and 46 (S3). The main discontinuities identified were projected, and the kinematic analysis highlighted potential failure modes involving sliding and toppling. For the various failure types, the SMR and CSMR scores generally correspond to stable to partially stable slopes, with the exception of wedges 1 and 2 at station S1, for which the failure probabilities are 0.6 and 0.9, respectively, indicating unstable to completely unstable slopes.

Keywords: Poponguine cliff, Slope stability, RMR, SMR, CSMR

INTRODUCTION

A landslide is the downward movement of a mass of rock, earth or debris down a slope [1]. It can be triggered by a variety of external stimuli, such as heavy rainfall, seismic activity, fluctuations in the groundwater level or storm surges. These stimuli cause a rapid increase in stress or a decrease in the shear strength of the materials forming the slope.

Regarded as one of the major natural hazards [2], landslides cause not only loss of life but also damage to infrastructure (road blockages, building collapses), loss of agricultural land and obstruction of watercourses [3].

The Poponguine cliff is situated on the coast and is home to the second presidential residence at its summit. Although the foot of the cliff is protected by a retaining wall, evidence of landslides can be seen along the entire length of the structure. These signs consist of stones and boulders that have fallen from the land above the retaining wall and indicate that the cliff is receding. An analysis of the failure modes is necessary to improve the management of landslide risk through the adoption of appropriate cliff stabilisation and/or monitoring techniques.

There are several methods for studying the stability of rock slopes, including the SMR methods, which are based on the RMR classification [4] and the kinematic analysis of failures using stereographic projection; these methods enable the probability of failure to be predicted and support techniques to be proposed. In this study, the discrete [5] and continuous [6] SMR methods were applied to characterise the instabilities of the Poponguine cliff.

LOCATION AND GEOLOGY

The cliff outcrops for around ten metres near the Presidential Palace, where the most complete cross-section has been mapped [7]. Located in Poponguine (Figure 1), the cliff consists of strata trending N130 and dipping 10° SW. It is cut by synsedimentary sandstone veins trending N15 and N60, with a dip of 70° to the west. Millimetre-scale veins filled with calcite and trending N60 are also present, often offset by the aforementioned veins. The lithological sequence (Figure 2) is subdivided into three units [7] associated with the Ndayane Formation [8 and 9].

Unit 1, 2.50 m thick, consists of grey calcareous clays with marl-calcareous lenses at the top, cut in all directions by small gypsum veins.

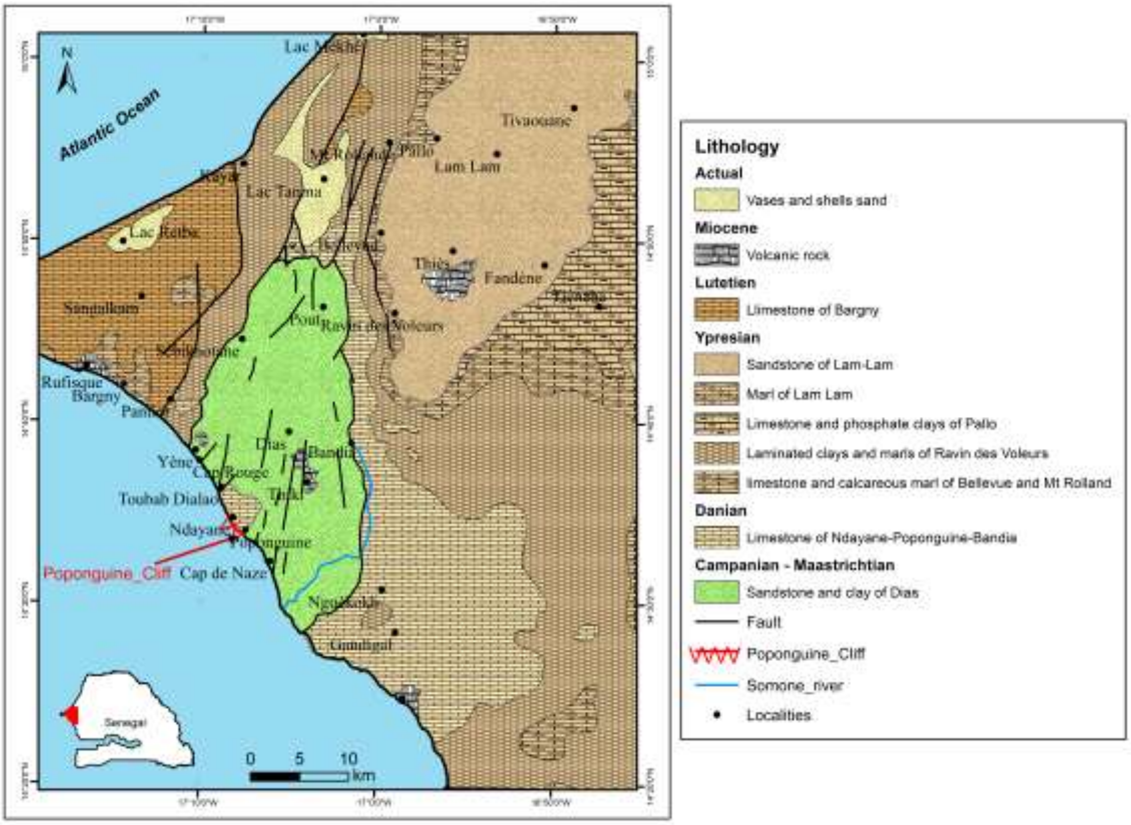


Figure 1 - Lithological map of the study area [10], modified [11]

Unit 2, which is 17.50 m thick, consists of alternating limestone beds and yellowish marl-limestone beds, also cut by small gypsum veins. The limestone beds are thin and lenticular at the base (10–40 cm thick); they thicken towards the top (70–90 cm), where the marl-limestone beds in turn become lenticular. The top two metres consist of thinner limestone beds (10–20 cm) with thicker marl beds (40–60 cm). Numerous sedimentary deformation structures are observed within this marl-limestone unit. The most common are found at the base of the limestone beds: load casts, which can reach up to 50 cm in diameter, and flame-like structures. Others, such as ball and cushion structures, are rarer. This unit outcrops extensively above the retaining wall and was the subject of this study.

Unit 3, 10 m thick, consists of marls with calcite rosettes, containing thin marl-limestone lenses at their bases.
The succession yielded a rich and varied microfauna comprising planktonic and benthic foraminifera and ostracods. It is dated to the Danian based on the presence of *Morozovella trinidadensis* (biozones P1–P2) [7].
The discontinuities consist of faults with low displacement (less than 10 cm) but, above all, of joints.

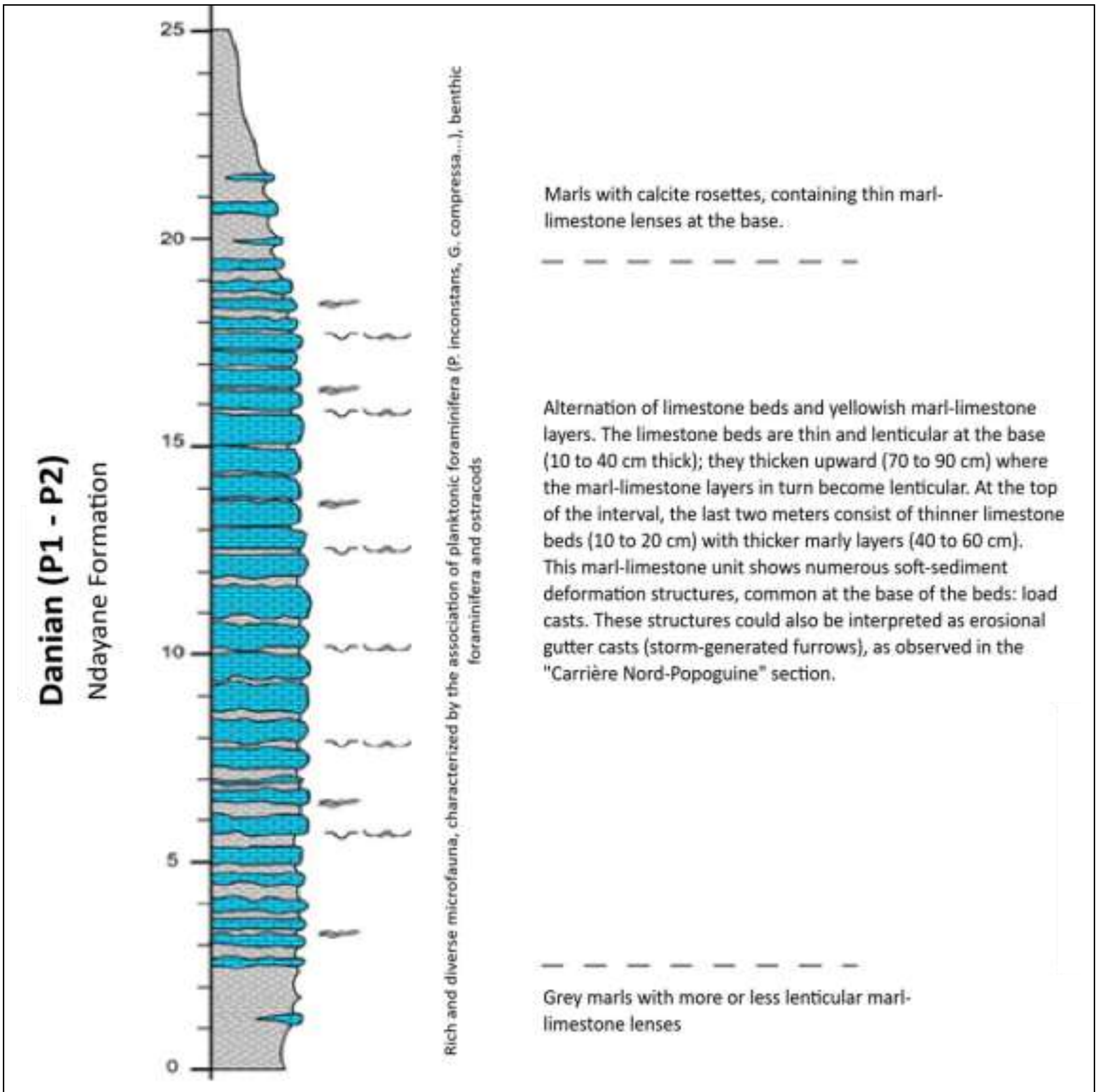


Figure 2 – Cross-section of the Poponguine cliff [7], modified [9]

METHODOLOGY

Based on the thickness of the limestone beds, the density of fractures and the degree to which the terrain is exposed to sea spray – which gives the rocks a different appearance – the outcrop is subdivided into three (03) stations. At Station 1 (Figure 3.a), the outcrop faces south-east and receives virtually no sea spray. The limestone beds are on average 30 to 50 cm thick and are heavily fractured. At Station 2 (Figure 3.b), the slope dips towards the south-west. It receives some sea spray, which gives the rock a damp appearance. The limestone beds are 50 to 70 cm thick and are less fractured than those at Station 1. Station 3 (Figure 3.c) is characterised by limestone beds that protrude significantly above the marl layers. The slope faces the shore and the degree of exposure to sea spray is very

high. This explains why the marl beds have been eroded more markedly than the more resistant limestone beds. The limestone beds are on average 50 to 70 cm thick and are fractured. The fractures are filled with marl, gypsum, calcite or silica.
The SMR and CSMR classifications were applied at each station. SMR and CSMR are based on the RMR classification [4]. The RMR classification involves the assessment of five basic parameters: i) rock compressive strength (UCS), ii) the RQD index, iii) the spacing of joints, iv) the condition of joints, and v) hydraulic conditions. For each parameter, a coefficient is assigned, and the sum of the coefficients determines the RMR value, which can range from 0 to 100. This RMR value may be adjusted by a sixth parameter depending on the orientation of the joints (Table 1).

Table 1. Rock mass classification [4] in [12]

Parameter	Range of values							
UCS	Values	>250 MPa	100 - 200	50 - 100	25 - 50	5-25	1- 5	<1
	Rating	15	12	7	4	2	1	0
RQD	Values	90 – 100%	75 – 90%	50 – 75%	25 – 50%	<25%		
	Rating	20	17	13	8	3		
Joint Spacing	Values	>2000 mm	600 – 2000 mm	200 – 600 mm	60 – 200 mm	<60 mm		
	Rating	20	15	10	8	5		
Joint Condition	Values	Very rough surfaces No continuous No separation Unweathered wall	Slightly rough surfaces. Separation < 1mm Slightly weathered wall	Slightly rough surfaces. Separation < 1mm. Highly weathered wall	Slickensided surfaces OR gauge < 5 mm thick OR separation 1-5 mm	Soft gauge > 5 mm OR Separation > 5 mm Continous		
	Rating	30	25	20	10	0		
Groundwater		Completely dry	Damp	Wet	Dripping	Flowing		
	Rating	15	10	7	4	0		

Considering the adjustment of the RMR value based on the orientation of the discontinuities to be too significant (the adjustment value can be as low as -60 out of a maximum RMR score of 100), [13] proposed improvements to the RMR to adapt it to slopes, resulting in the SMR (table 2). The SMR value is obtained by adding adjustment factors to the RMR value. These factors depend, on the one hand, on the relative orientation of the joints and the slope, and, on the other hand, on the excavation method used.

$$SMR = RMR + (F_1 \times F_2 \times F_3) + F_4 \qquad (1)$$

- F1 depends on the orientation of the joints relative to the direction of the slope. It takes values between 0.15 and 1. It is given by the following equation (equation 2):

$$F_1 = (1 - \sin A)^2 \qquad (2)$$

A represents the angle between the dip direction of the slope and that of the joints.

- F2 refers to the dip of the joints in plane-failure. Its value ranges from 0.15 to 1 and is given by the following equation (equation 3):

$$F_2 = tg^2 Bj \qquad (3)$$

For toppling, F2 will be set to 1

Table 2. Stability classes as per SMR values [13].

Class	I	II	III	IV	V
SMR	81-100	61-80	41-60	21-40	0-20
Rock mass Description	Very good	Good	Normal	Bad	Very bad
Stability	Completely stable	Stable	Partially stable	Unstable	Completely unstable
Failures	None	Some block failure	Planar along some joints or many wedge failure	Planar or big wedge failure	Big planar or soil-like or circular
Probability of Failure	0	0.2	0.4	0.6	0.9

- F3 depends on the relationship between the dip angles of the slope (βs) and the discontinuities (βj) (planar failure and toppling) or between the dip angle of the slope and the dip angle of the line of intersection of the discontinuities (βi) (wedge-type failure)
- F4 is an adjustment factor that depends on the excavation method and is determined empirically.

Some authors have modified or adapted the 1985 SMR version. These modifications relate to both the application methodology and the determination of correction factors [14]. Anbalagan and al. (1992) [15] suggested an adaptation of the SMR for wedge-type failure. They proposed calculating the geometric relationships between the discontinuity and the slope to obtain the values originally proposed by Romana [13], using the line of intersection of the two planes originating from the wedge. Tomás and al. (2007) [6] proposed continuous asymptotic functions for the correction factors F1, F2 and F3 (Table 3), which show maximum absolute differences of less than 7 points compared with the original discrete functions, thereby significantly reducing the subjective nature of scoring for values close to the boundaries of the discrete classification intervals. These functions are very useful for implementation in computer programmes for calculating SMR; this is the case with the calculator developed by [16], which was used in this study.

Table 3. CSMR adjustment factors [6]

Ajustment factors	*Plane Failure*	*Toppling*
F_1	$F_1 = \frac{16}{25} - \frac{3}{500} a\tan\left(\frac{1}{10}(\lvert A\rvert - 17)\right)$	
F_2	$F_2 = \frac{9}{16} + \frac{1}{195} a\tan(\frac{17}{100} B - 5)$	$F_2 = 1$
F_3	$F_3 = -30 + \frac{1}{3} a\tan C$	$F_3 = -13 - \frac{1}{7} a\tan(C - 120)$

RESULT AND DISCUSSION

RMR classification of the Poponguine Cliff

At station 1, the limestone rock mass has an average compressive strength of 23.6 MPa, which corresponds to a rating of 2. The RQD is 61.71 per cent, indicating rock of average quality and allows a score of 13 to be assigned to the massif for this parameter. The average joint spacing is 113.05 mm (ranging from 60 to 200 mm), which places it in the closely spaced joint class and allows a score of 8 to be assigned. The joints have slightly rough faces and are moderately weathered. Their persistence is low (length = 1.27 m). The average opening is 19 mm (very widely opened joints). The filling material is soft (marl) with a thickness greater than 5 mm. The combination of these sub-parameters results in a score of 10 for the nature of the joints. A score of 15 is assigned to the groundwater parameter as the rock mass is dry. Ultimately, the rock mass rating (RMR) at Station 1 is 48, which corresponds to Class III, denoting a rock of medium quality (Table 4).

At Station 2, the limestone rock mass has an average compressive strength of 19.1 MPa, which corresponds to a score of 2. The RQD is 73.54 per cent, indicating rock of average quality and resulting in a score of 13 for the massif for this parameter. The average spacing of the joints is 132.25 mm (ranging from 60 to 200 mm), which places it in the class of closely spaced joints and results in a score of 8. The joints have slightly rough faces and are moderately weathered. Persistence is very low (length = 0.87 m). The average opening is 32 mm (very widely open joints). The filling material is soft (marl) with a thickness greater than 5 mm. The combination of these sub-parameters allows a score of 10 to be assigned for the nature of the joints. A score of 15 is assigned to the groundwater parameter as the rock mass is dry. The RMR score for the rock mass at Station 2 is 50, which corresponds to Class III, denoting rock of medium quality (Table 4).

a – Station S1

b – Station S2

c – Station S3

Figure 3. ***– Application stations for the RMR, SMR, and CSMR systems at the Poponguine Cliff [17]***

At Station 3, the limestone rock mass has an average compressive strength of 21.2 MPa, which corresponds to a score of 2. The RQD is 70.36 per cent, indicating rock of average quality and resulting in a score of 13 for the massif for this parameter. The average spacing of the joints is 166.26 mm (ranging from 60 to 200 mm), which places them in the class of closely spaced joints and results in a score of 8. The joints have slightly rough and heavily weathered rims. Persistence is low (length of 2.56 m). The average opening is 55 mm (very widely open joints). The filling material is soft (marl) with a thickness greater than 5 mm. The combination of these sub-parameters results in a score of 8 for the nature of the joints. A score of 15 is assigned to the groundwater parameter as the rock mass is dry. The rock mass rating (RMR) at Station 3 is 46, which corresponds to Class III, indicating rock of medium quality (Table 4).

Table 4. – RMR classification of the Poponguine Cliff

Station	UCS	RQD	Joint Spacing	Joint Condition	Groundwater	RMR	Class/ description
S1	2	13	8	4+0+3+3+0 = 10	15	48	III/ medium quality
S2	2	13	8	6+0+3+3+0 = 12	15	50	III/ medium quality
S3	2	13	8	4+0+3+1+0 = 8	15	46	III/ medium quality

Despite differences in the surface appearance of the rocks at Poponguine, the RMR varies only between 46 and 50, which means that the rock masses belong to the same Class III. The small difference between the RMR scores is due to the condition of the joints, which are less persistent at Station 2.

SMR and CSMR classifications for the Poponguine Cliff

The SMR and CSMR classifications are applied to the same stations as the RMR. The dip and the dip directions of the slopes and joints are listed in Table 5.

Table 5. – Orientations of slopes and joints measured in Poponguine

Station	Slope (Dip/Dip direction)	Joints	Dip (β)	Dip direction (α)
S1	86°/172°	J1	88°	232°
		J2	82°	92°
		J3	54°	80°
		J4	68°	232°
S2	88°/246°	J1	36°	138°
		J2	14°	122°
		J3	70°	290°
S3	54°/264°	J1	28°	110°
		J2	68°	102°
		J3	70°	148°
		J4	60°	324°

At station S1, the RMR value is 48. The slope faces south-east (dip direction N172°) and has a dip of 86°. Four families of discontinuities – J1, J2, J3 and J4 – were identified (Table 5). The station presents three potential wedge failure zones, designated wedge 1, wedge 2 and wedge 3 (Figure 4).

Wedge 1, formed by the intersection of J1 and J2, has a dip of 75° and a dip direction of N149°. The SMR and CSMR calculated for Wedge 1 are Class IV, indicating an unstable slope with a failure probability of 0.6.

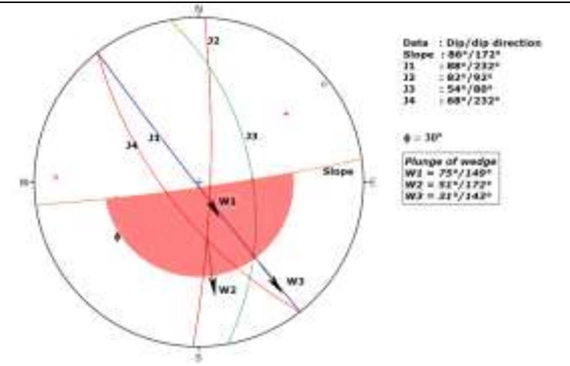
Wedge 2, formed by the intersection of J2 and J4, has a dip of 51° and a dip direction of N172°; the slope is completely unstable (SMR and CSMR of Class V and a failure probability of 0.9).

For wedge 3, formed by the intersection of J1 and J3, the slope is partially stable with a probability of failure of 0.4 (Table 6).

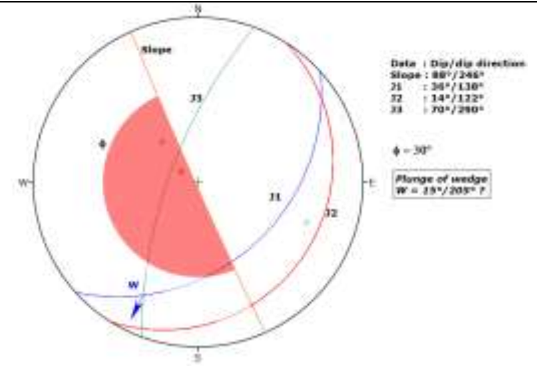
At station S2, the RMR rating is 50. The slope faces SW (246° dip direction) and has a dip of 88°. Three types of discontinuities – J1, J2 and J3 – have been identified (Table 5). The most likely failure modes are slides on the preferential plane J3. The SMR and CSMR calculated for a slide along plane J3 are Class III, indicating a partially stable slope (Figure 4). With regard to potential overturning, which would be caused by J2, the slope is stable. The wedge formed by the intersection of J1 and J3 has a dip of 15°, which is less than the angle of friction and is therefore stable (Table 6).

The RMR score is 46 at Station 3. The slope faces SW (264° dip direction) and has a dip of 54°. Four families of discontinuities – J1, J2, J3 and J4 – have been identified (Table 5). The most likely failure modes are toppling failures caused by J1 and J2. The slope is partially stable with regard to toppling caused by J2 and is stable with regard to toppling caused by J1 (Figure 4).

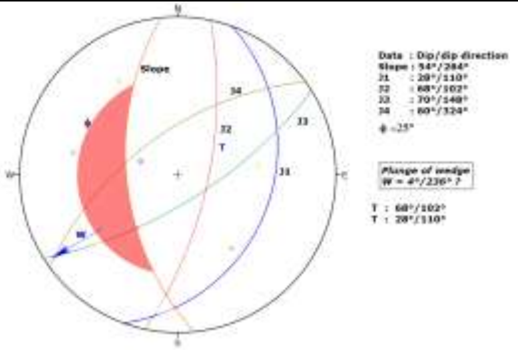
The slope is partially stable with regard to planar failures that would be caused by J4 and wedge-type failures caused by the J3–J4 intersection (Table 6).



S1



S2



S3

Figure 4. Plot of joints and slope at locations S1, S2, and S3. The pink coloured area indicates the critical zone of failure. The symbols used in figure are as, J1, J2, J3, and J4: Orientation of joints; W1, W2 and W3: Wedge formed by intersection of joints; T: Toppling.

Table 6. – SMR [5] and CSMR [6] classification of the Poponguine Cliff

Station	RMR	Slope (Dip/Dip direction)	Probable failure	Dip (β)	Dip direction (α)	SMR					CSMR					Class/Stability
						F1	F2	F3	F4	SMR	F1	F2	F3	F4	CSMR	
S1	48	86°/172°	**Wedge 1**	**75°**	**149°**	**0.4**	**1**	**-60**	**15**	**39**	**0.45**	**0.99**	**-58.27**	**15**	**37**	**IV/Unstable**
			Wedge 2	**51°**	**172°**	**1**	**1**	**-60**	**15**	**3**	**1**	**0.95**	**-59.45**	**15**	**7**	**V/ C. Unstable**
			Wedge 3	31°	143°	0.4	0.7	-60	15	46	0.34	0.64	-59.65	15	50	III/P. Stable
S2	50	88°/246°	Wedge	15°	205°	0.15	0.15	-60	15	64	0.24	0.21	-59.74	15	62	II/Stable
			Planar	70°	290°	0.15	1	-60	15	56	0.22	0.98	-58.94	15	52	III/P. Stable
			Toppling	14°	122°	0.15	1.0	0	15	65	0.19	1	-60	15	65	II/Stable
S3	46	54°/264°	Wedge	4°	236°	0.4	0.15	-60	15	57	0.35	0.17	-59.62	15	57	III/P. Stable
			Planar	60°	324°	0.15	1	-6	15	60	0.18	0.97	-3.15	15	60	III/P. Stable
			Toppling 1	28°	110°	0.4	1	0	15	61	0.39	1.0	-0.36	15	61	II/Stable
			Toppling 2	68°	102°	0.7	1	-25	15	43	0.61	1.0	-22.06	15	48	III/P. Stable

CONCLUSION

At Poponguine, the orientations of the discontinuities relative to the slopes make it possible to predict failures such as plane sliding, simultaneous two-plane sliding (wedge) and toppling. The RMR classes assign an intermediate quality to the rock. The SMR and CSMR classes range from II to V. Of the three sites, only site S1 is considered unstable, with SMR and CSMR classes of IV and V, corresponding, respectively, to failure probabilities of 0.6 and 0.9, and requiring reprofiling or stabilisation. The slopes at stations 2 and 3 are considered partially stable and require regular monitoring.

Declaration by Authors

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