Stability Assessment of High Cliff Slopes in Carbonate Rocks - A Case Study, Kingdom of Saudi Arabia (KSA)

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Abstract: This study evaluates the stability of high cliff slopes along a 1 km long carbonate–volcanic ridge in the Kingdom of Saudi Arabia. Geological mapping, satellite imagery, and over 350 joint measurements were used to characterize rock mass conditions across three zones. Rock mass ratings and direct shear tests provided inputs for kinematic and analytical stability assessments using Rocscience and Slope/W. Results indicate potential planar, wedge, and toppling failures controlled by key joint sets, with global factors of safety of about 1.5 (static) and 1.2 (dynamic). A 1–1.5 m distressed zone was identified along the cliff edge, and Safe Working Line (SWL) distances were recommended considering a 250 kPa surcharge. The study provides essential guidance for safe development near steep rock escarpments.

Keywords: Rock slope stability, Kinematic analysis, Carbonate rocks, Safe Working Line (SWL), Saudi Arabia.

Introduction

The geological mapping of the ridge/ cliff was carried out to characterize and classify the rock mass, besides checking out the stability of the cliff sections. The study area along a ridge of about 1 km in length covering about 450,000 m^{2}area. The site is distinctly marked by the presence of an NNE–SSW trending ridge with cliff face of about 70-100 m in height (Figure 1). The hilltop is 50-100 m wide with sloping surfaces at an angle of 55–70°. Two lineaments trending E-W cut across the hill ranges and divide the ridge into Z1, Z2 and Z3 (Figure 2).

Figure 1, Google image showing project Layout.

Figure 2, Google image showing zones distribution.

Geology and Site Condition

The study area falls under Shimmer Rhyolite Group which mainly comprises of andesite, diorites and rhyolites and its variants, and intervening sediments which may be shales dolomitic limestone etc. The ridge exposes locally the thick meta-igneous/igneous plutonic/ dykes swarms underlain by basaltic flow deposits of 3–4.5 m thick andesite/ volcanic rocks with a 1–3 m thick top capping of interbedded/ coralline limestone is noticed. Other than these non-sedimentary rocks, a thickly bedded sandstone and calcareous sandstone/calcarenite with basal conglomerates are exposed on the western side of the project site. Terrace deposits of approximately 1–1.5 m thickness are seen at the foot hill reaches.

Methodology

The methodology included acquisition of field data, including geological mapping aided with the satellite imagery to decipher the presence of geological features like faults, shear zones, discontinuities with their orientation with respect to the escarpment. The azimuthal data of the discontinuities/ joints were collected; besides, the joint parameters/ features. Additionally, laboratory testing like direct shear tests along the identified potential discontinuities were also performed. The data was further synthesized using the Rocscience software's to check the kinematic admissibility to identify the failure modes and the potential blocks. Analytical checks for the potential blocks were also carried out along with global stability checks using slope/W programme, using a FEM model study- circular failure analysis targeting a Safety Factor of 1.5 and 1.2 for static and dynamic conditions.

Rock Mass Characterization

RMR and GSI were performed with the available mapping and testing data (Brown, 1981). Estimation of shear strength parameter values of c and ø were estimated by the GSI and UCS values by using the roc-lab software is given in Table1.

Slope Stability Assessment

The Kinematic Admissibility Check for all three zones was carried out. Over 350 discontinuity/joints data were collected from the three zones (Figure 3). The stereo analysis was carried out with Rocscience suite of software i.e. Dips7, SWEDGE, roc plane, Roc topple.

Results

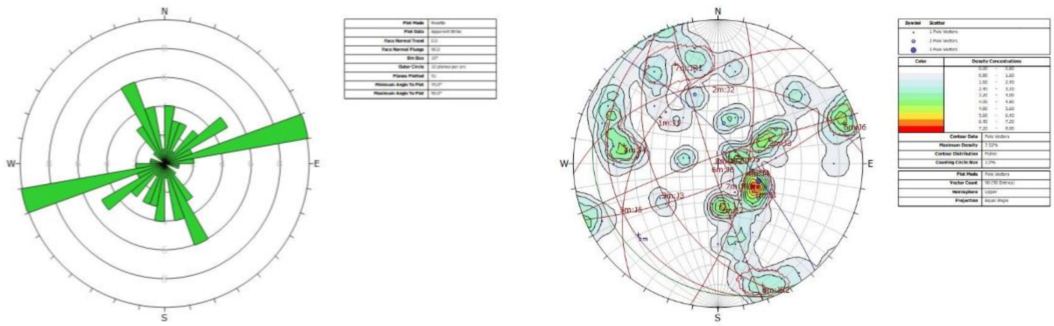
In zone 1 and zone 2, total eight joint sets are identified, of which six (6) are major and two (2) are random joint sets. However, in zone 3, total nine (9) joints sets are identified, out of which, eight (8) are major and one (1) is random joints. A summary of the identified potential blocks for the different slopes was identified and typical one is shown in Table 2.

The analytical checks for a FOS of 1.5 and 1.2 in static and dynamic conditions were carried out adopting the Allowable/ workable Stress Design (ASD) method as per BS standards and parameter used for zone -1 is presented in Table 3. The adopted shear strength parameter (Ø) and γ values are taken from direct shear tests along the rock joints.

The output from the Kinematic admissibility checks for zone 1 and 2 revealed that J1, J3, JR1 and JR2 are potential for planar and wedge failure whereas J1, J3 and J5 form the base planes for flexural toppling failure with J4 joint set and the direct toppling failure block. In zone 3, J2, J3, JR1 pose plane block failure whereas J2, JR1 form the base planes for direct toppling failure. A summary of the results of zone-1 is given in Table 4.

Table 1, Summary of the RMR and GSI based estimations.

Rock mass category	RMR value Range	Average GSI value considered	Cohesion C (MPa)	Friction angle ø (°)
RM- 1	55 – 60 (Fair, class III)	58	2.92	40.85
RM -2	60 – 65 (Good, Class II)	63	3.129	42.34
RM- 3	25 – 30 (Poor, Class IV)	28	0.280	31.74



Typical Rose Diagram Typical Contour Diagram

Figure 3, Dips analysis outputs for zone-1.

Table 2, Typical summary of potential blocks of zone 1.

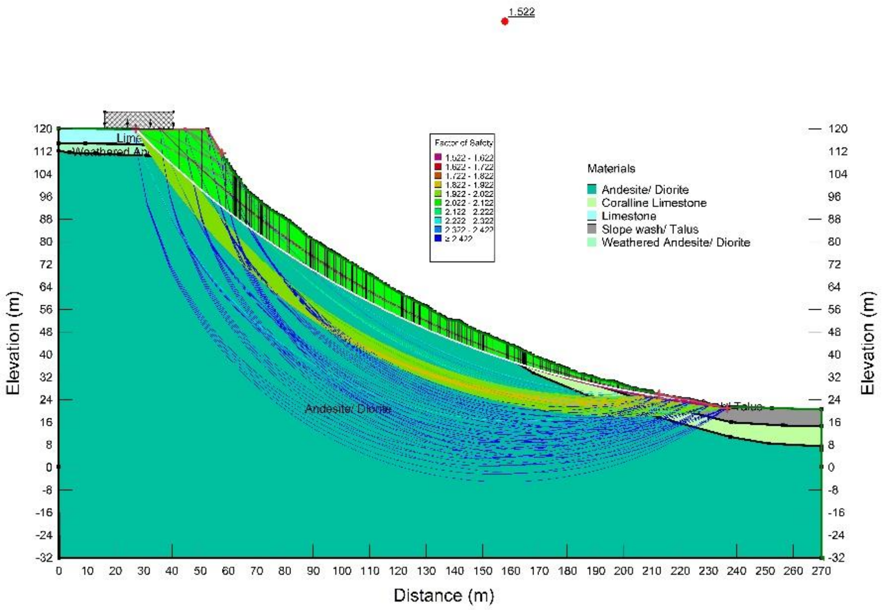
Slope	Type of Potential Blocks	Block ID - Joint sets
Eastern Slope	Planar (P)	Z1EP1- J1, Z1EP2- J3
	Wedge (W)	Z1EW1- J3 Vs JR1, Z1EW2 – J3 Vs JR2
	Toppling (T)	Z1ET1 - J4 Vs JR2
Western Slope	Planar (P)	NF
	Wedge (W)	NF
	Toppling (T)	NF/ very local

Table 3, Input parameters for analysis of zone-1.

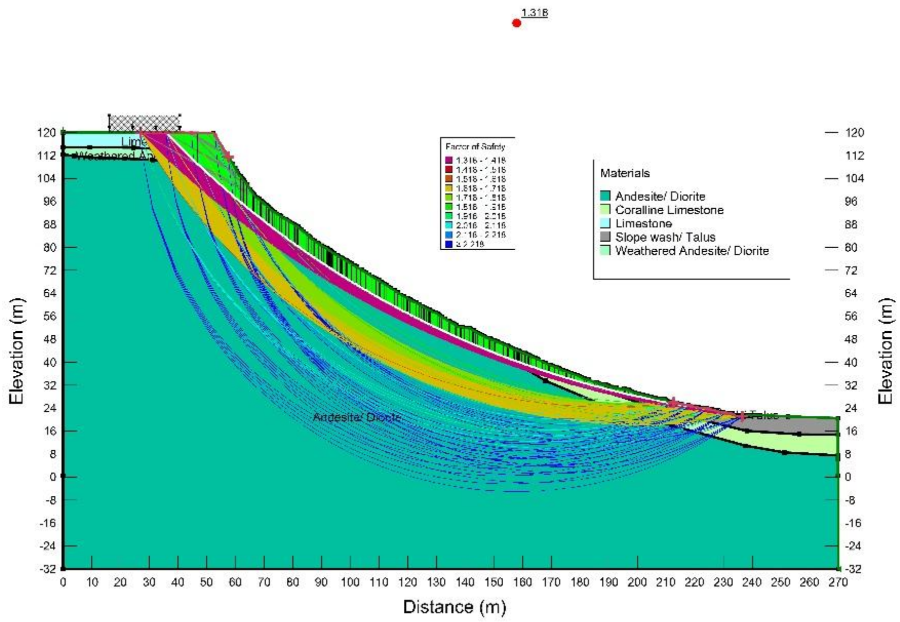
Slope.	Block ID	γ t /m³	C (t/m²)	Ø (°)	Surcharge load E (t) *	Slope height (m)	Slope directions	Water pressure (%)	Remarks
Zone-01	Z1P	2.5	0	32	25	10,20	080 & 300	60	
	Z1W	2.5	0	32	25	10,20		60	
	Z1T	**2.5**	**0**	**32**	**25**	**10**		**60**	

Table 4, Summary of analysis of zone-1 cut slopes.

Wedge/ Plane No.	Slope height (m)	FoS (1)	Slope Protection / Treatment Measures						Wedge Vol. (t/m3)	Wedge Wt. (t/m)	Remarks
			ROCK BOLT			Shotcrete (mm)	FoS(2)	FoS(3)			
			Bolt Length (m)	Anchor length (m)	Capacity (t/m)						
Z1EP1	10	0.527	5.0	1.90	60	-	>1.5	>1.2	42.15	105.37	Stable with stabilization measures
	20	0.473	10.0	2.03	210	-	>1.5	>1.2	168.59	421.46	
Z1EP2	10	0.142	2.0	1.41	52	-	>1.5	>1.2	11.79	29.48	
	20	0.000	3.0	1.70	154	-	>1.5	>1.2	47.17	117.93	
Z1EW1	10	0.904	3.0	1.48	150	-	>1.5	>1.2	241.70	604.27	
	20	0.904	3.0	1.50	150	-	>1.5	>1.2	241.70	604.27	
ZIEW2	10	0.867	5.0	2.56	250	-	>1.5	>1.2	502.52	1256.32	
	20	1.005	5.0	2.57	300	-	>1.5	>1.2	1179.48	2948.71	
			4.0	1.80	300						
Z1ET1	10	0.722	4.5	1.5	250	-	>1.5	>1.2	-	-	
Z1ET2	10	0.702	4.5	1.5	280	-	>1.5	>1.2	-	-	



Output- Static (FoS 1.522)



Output – Dynamic (FoS 1.318)

Figure 5, Typical W/Slope analysis outputs- Global outputs of global stability.

Table 5, Summary details of SWL.

Slope ID	Zone ID	Failure Mode	Potential block ID	Plunge (deg.)	Distance from cliff edge (m)	SWL from cliff edge (m)	Rec. SWL w/o stabilization measures	Load behind SWL (KPA)	Slope Angle (º)
EASTERN	Z1	Planar	Z1EP1	40	2.5	2.5 - 5	2.5 - 5	250	**70**
			Z1EP2	55	1			250	
	Z2		Z2EP1	40	2.5			250	
			Z2EP2	30	4.2			250	
	Z3		Z3EP1	40	2.5			250	
			Z3SP1	40	2.5			250	
	Z1	Wedge	Z1EW1	30	4.2	4 to 5		250	
			Z1EW2	34	3.8			250	
	Z2		Z2EW1	34	3.8			250	
	Z3		Z3EW1	32	3.7			250	
			Z3EW2	27	4.8			250	
	Z1	Toppling	Z1ET1	55	1	2.5 - 5		250	
			Z1ET2	35	3.5			250	
	Z2		Z2ET1	40	2.5			250	**70**
			Z2ET2	45	2			250	
	Z3		Z3ET1	30	4.2			250	
Southern	Z3		Z3ST1	37	2.9	2 to 3	2 to 3	250	**70**
			Z3ST2	55	1			250	
Western	Z3		Z3WT1	35	3.5	3 to 4	3 to 4	250	
			Z3WT2	45	2			250	
	Z1&Z2*		-	-	1 - 1.5*	2 – 2.5	2 – 2.5*	250	

Global Stability

Global stability checks, for the existing slopes, were carried out. The results with FOS of 1.5 and 1.2 for static and dynamic conditions were calculated (Figure 5).

Distressed zone

A distressed zone of 1–1.5 m along the cliff edge is noticed with manifestations of dilated/ gapping joints along with movement of blocks. Due to the relief stress cracks/ joints get dilated and new cracks develop parallel to the cliff line/ alignment.

Safe Working Line (SWL)

SWL is the distance considering surcharge of 250 kPa which can be safely adopted without any remedial/ stabilization measures. The details of SWL values is given in Table 5.

References

Brown, E. T. (1981). ISRM suggested methods for the quantitative description of discontinuities in rock masses. Pergamon Press.