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Evaluation of Stability of the Rock Slopes in Taiz City and Surrounding Areas of Yemen Using Slope Mass Rating (SMR) System and Kinematic Analysis Technique

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ABSTRACT
Assessment of stability of rock slopes is important to thwart the occurrence of landslides and consequent socio-economic evils. The present maiden study is carried out in and around Taiz city known for geotechnical hazards by isolating 14 of 110 field stations located along road cuts, quarries and natural exposures representing varying lithological and geotechnical conditions. The stability of rock slopes was evaluated by applying the original Slope Mass Rating (SMR) system. The parameters of SMR system were measured based on field and laboratory investigations. The failure mode at each site and its potential failure directions were determined kinematically using the stereographical projection method employing Stereonet software. The obtained results from applying SMR system at 14 rock slope stations demonstrated that there are various modes of failure and a single slope may have been affected by more than one type of failure depending on the relationship between the discontinuities and slope face, discontinuity characteristics and lithological conditions. The calculated values of SMR show variations from 1.4 to 70.4 indicating that these values plot from "Very Bad" (Vb) class to "Good" class (IIb). The results also indicate the more scope for planner, toppling and/or big wedge failures and warrants suitable corrective measures, especially in the areas where the SMR values fall in IV and V classes. Further, slope Nos. 5 (zone-I) and 40 (zone-I) are "Stable" against wedge and toppling failures respectively and five slope locations (22, 36, 68, 76 and 86) are "Partially Stable" against toppling failures, while two rock slope locations (Nos. 77, 92 and 96) are "Unstable" against the various failures. The unstable slope locations vulnerable for planar/falling failure are 5, 30, 57, 76 and 86. The remedial measures to control slope failures in 14 slope locations are suggested based on SMR values.
Keywords: Kinematic Analysis, Slope Mass Rating, Slope Stability, Taiz City in Yemen

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I. INTRODUCTION

Taiz area in Yemen is located adjacent to tectonically active rift zone known as Red Sea–Gulf of Aden rift system. This active zone can cause the reactivation of the old fault systems and may create new faulting lines and discontinuities (joints) in the Tertiary rock masses of area. The slopes in Taiz area developed over Tertiary rocks are well known for their instability due to the dynamic nature of slopes, lithology, anthropogenic activities, rainfall and ongoing neo-tectonic activities. Urbanization followed by unplanned rapid development of buildings and other infrastructure facilities have caused unfavourable changes in the configuration of Tertiary rock slopes causing landslides and also instability in the form of the development of cracks in the walls, foundation problems leading to collapse of the buildings (Fig.1), thus bringing undesirable socio-economic changes in the lives of the citizens. There are many landslides/collapses that occurred at different places in the study area. In 2010, unplanned excavation and vibrations caused by blasting at the foot slope of Amid Mountain, near Taiz University for the purpose of construction has enhanced the vulnerability of slopes to landslide. In order to provide safety both to the common man and the civil structures as well as to reduce the slope failures, slope characterization and evaluation of stability of the road cut slopes are required. The analysis of slope characterization depends upon many parameters and database related to slope, rock/rock mass, meteorology, etc. [1a, 1b, 2]. The stability of rock slopes is essentially governed by the joint sets, characteristics of joint materials, seepage pressure, and depth and steepness of the excavated slope face and its orientation with respect to the joint sets [3].

Slope mass characterization is necessary for geotechnical studies and it involves laboratory and field investigations of intact rock blocks and discontinuities or defects (e.g., joints, weak bedding planes, weak zones, planes, faults, etc) present in rock mass. The geomechanical behaviour of rock mass in situ is governed by characteristics of intact rock and discontinuities on the one hand and their occurrence in the environment with many natural complexities on the other.

Fig.1 Photographs showing dilapidated conditions of buildings underlain by Tertiary volcaniclastics in the study area [4]

Due to complexity of rock mass with varying physico-mechanical in situ properties, numerous classification systems have been developed for the characterization, classification as well as to gain the knowledge on the rock mass properties and also to provide a quantitative valuation of rock mass by a simple arithmetic algorithm [5]. Most of these classification systems were originally applied in tunnels and underground mining (e.g. Q, RMR and MRMR systems). Some classification systems, originally developed for underground excavations have been used directly (e.g., Q and RMR system) or have been modified (e.g., the RMS, SMR, SRMR and CSMR systems comprise modifications of the RMR system) for the assessment of the stability of the slopes [6]. Among the classification systems which come with relevant recommendations for the remedial measures, the SMR [7] technique derived from basic RMR [8,9] is widely used to identify the potentially hazardous rock cut slopes.

In the present work, slope stability studies were conducted at 14 rock slope stations applying rock mass rating (RMR) and original slope mass rating (SMR) systems. Kinematic analysis was also carried out for the identification of mode of failure and its directions in these sites, in addition to the evaluation of the geotechnical properties of rock/ rock mass.

II. STUDY AREA

Taiz city is located on the south-western part of Yemen in the watershed area of upper Wadi Rasyan covering foothill and slope regions of Sabir Mountain and the area is bound by the latitudes; 13° 31' 49" and 13° 44' 29" N, and longitudes; 43° 54' 17" and 44° 09' 04" E (Fig. 2). Topographically, the study area is well represented by mountains, isolated hills, steep slopes, undulating eroded lands with major wadis, and plains and loess covered plateau (Al-Janad Plateau) with elevations ranging from about 800 m to 3000 m above mean sea level. According to the Meteorological data, the annual rainfall in the investigated area is bimodal; the first season starting from April to June with peak in May and the second is from August and October with peak in September.

The average annual rainfall in the study area is approximately 520 mm [10]. Climate data shows that the average monthly temperature in the study area is low during dry period from October to March while it goes up during the rainy season. Low temperatures are recorded during the dry months from mid-October to mid-March, with mean maximum temperatures in the range of 25.57° to 29.63 °C. High temperatures are recorded during the wet months from mid-March to mid-October, with mean maximum temperatures varying from 30.47° to 32.60 °C [10].

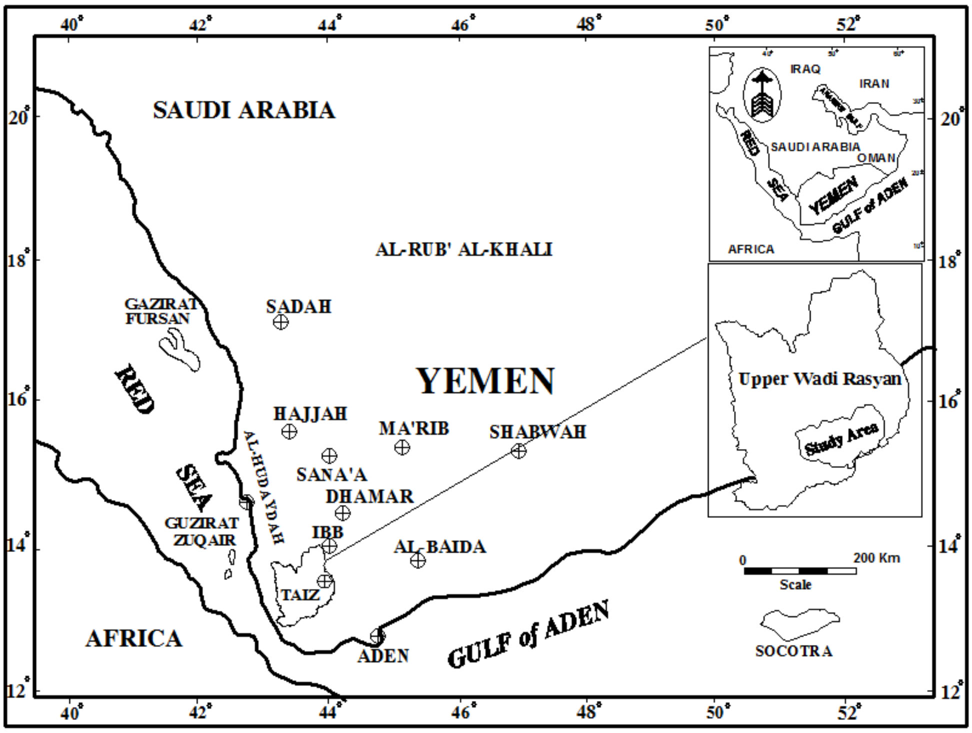


Fig.2 Location map of the study area

The rock masses of the Taiz area belong to Tertiary bimodal volcanic materials and their associated intrusive bodies (i.e., Sabir granite). The Tertiary bimodal volcanic materials are represented by alternating sequences of volcanic lava flows and volcaniclastic deposits of variable composition ranging from mafic to the silicic types. The sequence of volcanic lava flows and volcaniclastic deposits are the product of Red Sea – Gulf of Aden rift tectonics that was erupted in five phases [11, 12a, 13] and in a repeated manner. The flow sequences from bottom to top comprise (Fig. 3):

1) Tertiary lower mafic flow (Tb1, Eocene)
2) Tertiary lower silicic sequence phase (Tr1, Eocene -Oligocene)
3) Tertiary middle mafic sequence phase (Tb2, Oligocene-Miocene)
4) Tertiary upper silicic sequence phase (Tr2, Oligocene-Miocene)

Tb1 is represented by dark grey to chocolate brown (in fresh surface) or dark reddish brown (on outer weathered/altered surface) coloured jointed/ massive basaltic lava flows with basaltic volcaniclastic materials. Often the jointed basaltic lava flows are interbedded /alternated with basaltic volcaniclastic materials. These rocks are marked by different types of discontinuities as evidenced by the development of irregular joints, columnar joints, (thermal origin) in addition to other discontinuities in them. The rock blocks formed by these joints occur in various sizes and shapes such as columnar, polyhedral, tabular, prismatic and rhombohedral blocks.

Tr1 forms rhyolitic/ ignimbritic plateaus and rarely small hills in the study area. Petrologically, Tr1 is represented by jointed rhyolites / dacites, ignimbrites, rhyolitic tuffs, lapillistones, volcaniclastic breccias, and random pumice and obsidian [14]. Higher amounts of volcaniclastic rocks in Tr1 sequence indicate that initially volcanism was more explosive [13]. Vertically, this sequence shows change in lithology and colonnade columnar jointing features.

Tb2 is represented by basaltic lava flows and volcaniclastic deposits extruded primarily through the feeders like - dykes. Volcaniclastic deposits of this phase are classified into tuff-breccias, lapillituffs, agglomerates and lapillistones based on their particles sizes [14]. In the study area, the rocks and deposits of Tb2 have a greatest areal extent in comparison to all other units with thickness reaching up to 100 m and covering 39.61 % of the total area. These lava flows show different physical characteristics (colour, heterogeneity, discontinuity, thickness, horizontal attitude, weathering/alteration, intercalation and repetition with depth) both in vertical and horizontal directions implying variation in eruption type, mode of transport, distance travelled from the vent, temperature of the deposits, particle size, water content and paleorelief of older Tr1 sequence [14].

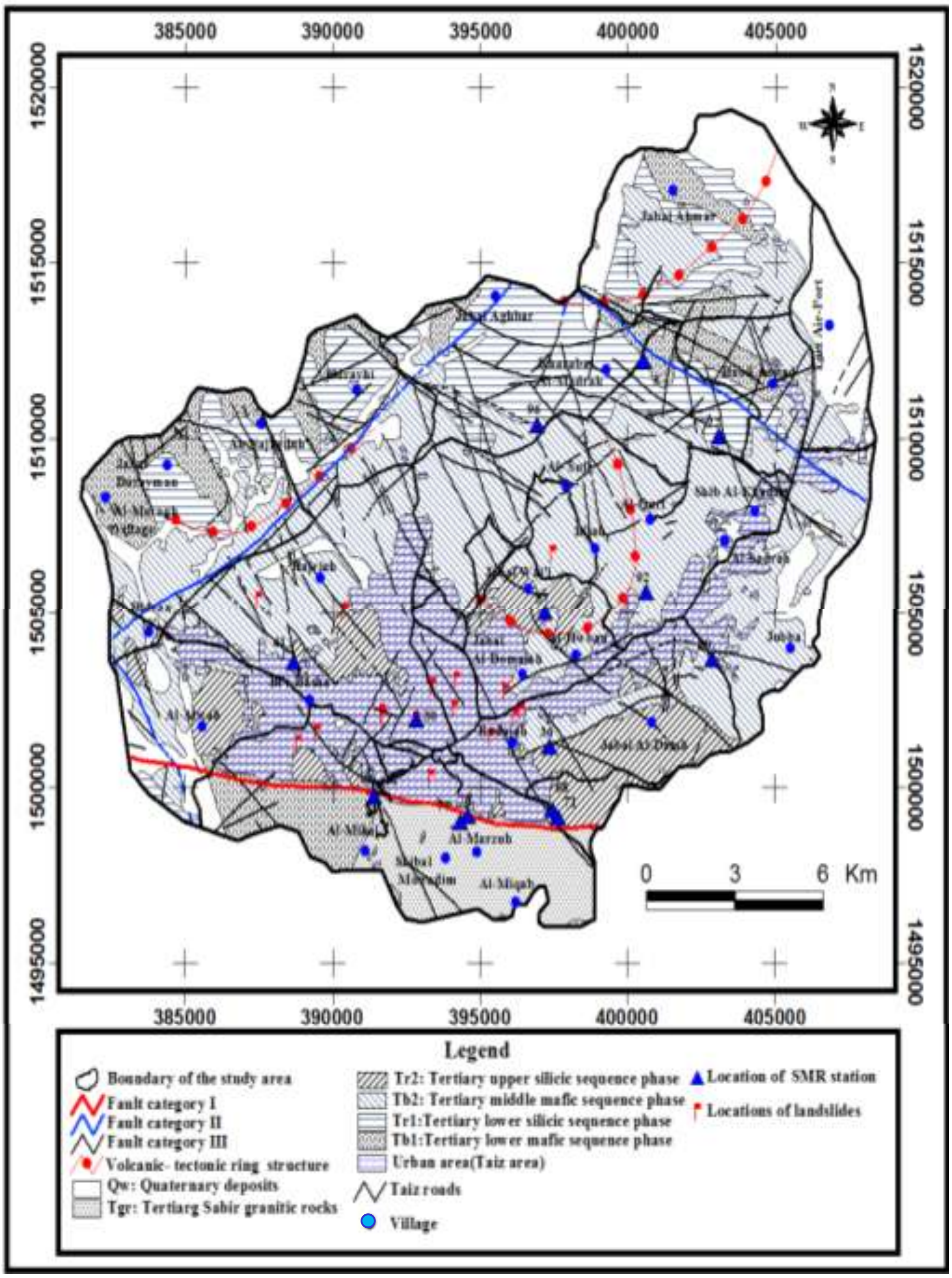


Fig. 3 Geological map of the study area (modified after [15, 12b, 13, 14]) with locations of the investigated stations

The outcrops of Tr2 sequence are limited and restricted into the vicinities of the Taiz city along the E-W Sabir fault system. The rocks constitute isolated domal mountains and plugs of different sizes and shapes. It covers an area of 41.47 sq.km (10.6%) of the total area. Tr2 is represented by fine-grained, porphyritic, yellow to gray, white, red, green and pink coloured jointed /massive rhyolites / dacites and/or varicolored volcaniclastics of rhyolitic composition. Volcanic pitchstone is also observed in different locations as lava flows or as irregular bodies intercalated with volcaniclastic materials. Volcaniclastic materials of the study area are classified based on their particle sizes into ignimbrites, rhyolitic tuffs, rhyolitic lapilli-tuffs and rhyolitic lapillistones [14]. The most characteristic feature of Tr2 is its occurrence as alternating sequence of more than one lava flow with variations in physical properties both in horizontal and vertical directions even in the same location.

Tertiary Sabir granitic pluton (Tg) is emplaced as laccolithic body inside the older stratified Tertiary Yemen volcanic rocks, forming the dominant morphological feature i.e., Sabir Mountain over- looking the city of Taiz in the southern part of the study area (Fig. 3). It is characterized by high lands, steep slopes and deep valleys. Physical weathering of varying intensities has produced different sizes of granitic blocks and boulders along the slopes. It consists mainly of massive, white to greyish white coloured, medium to coarse-grained grading up to granite porphyry with almost < 5 % of dark minerals alkaline or peralkaline granite. The rocks belong to the alkaline or peralkaline suite of A-type granites [16]. These are produced by fractional crystallization in the basic magmas [17, 18]. For the assessment of the stability of the slopes in and around Taiz city (Table 1), fourteen slope locations representing various rock types with heterogeneous geotechnical properties were chosen.

III. METHODOLOGY

1.III Field Investigations

Reconnaissance survey carried out throughout the Taiz area facilitated the selection of 110 locations along road cuts and on the natural rock outcrops. Detailed field and laboratory studies at 110 locations restricted the present slope stability assessment to 14 rock slope stations representing diverse lithological and geotechnical conditions. On these exposures, the field scanline survey technique [19a, b] was applied in three dimensions (as far as possible) to obtain the structural data related to Rock Mass Rating (RMR) system such as discontinuities (joints) characteristics and their conditions as well as the attitude of slopes (dip [βs] and dip direction [αs]).

Table 1 Locations and lithologies of the investigated slopes

Slope St. No.	Zone	Location of slope St. (UTM)		Lithology
		X	Y	
5	I	400541	1512209	Columnar ignimbrite
22	I	403089	1510046	Columnar basalt
30	I	392845	1501936	Rhyolitic tuff
36	I	397372	1501152	Massive rhyolite
41	I	388696	1503570	Jointed rhyolite /dacite
50	I-2	402880	1503642	Jointed basalt
57	I	397213	1504993	Columnar rhyolite
68	I	397474	1499345	Jointed rhyolite
71	I	397665	1499131	Jointed rhyolite
76	I	394593	1499194	Granite
77	I	394331	1499004	Granite
86	I	391404	1499751	Granite
92	II	400629	1505592	Jointed basalt
96	I	396934	1510372	Columnar basalt

For each discontinuity (joint) intersecting the scanline the following characteristics/ measurements are recorded: orientation or attitude of discontinuity ([βj] / [αj]) with respect to slope, spacing, persistence (m), aperture (mm), roughness, state and thickness of filling material, water flow and wall weathering. Procedures recommended by ISRM (1981a) (Table 2) were followed to measure and record the field data. The discontinuity orientations data ([βj] / [αj]) obtained in the field were plotted stereographically (equal-area stereographic projection) using computer software, called Rock Works /14 [20] and the joint sets were distinguished for all scanline surveyed data and then the pole concentrations were contoured. The maximum density points or mean density on the contour diagram were selected as the best representation of the average orientation of each discontinuity set (Table 2). The orientations of main discontinuity (joint) sets ([βj] / [αj]) and orientation of each slope ([βs]/ [αs]) were used in the calculation of SMR (Table 3) and the same were used to perform kinematic analysis to identify the mode of potential failure. The identification of the (i) mode of failure was done by re-plotting βj and αj of the recognized main joint sets of each rock slope station on the stereo-net using RockWorks/14 software [20] and (ii) potential unstable zones in the slopes employing stereo-net software, version 9.2.1 [21] (Fig. 4).

The internal friction angle (Ø°) of each rock mass used for kinematic analysis has been estimated based on the RMR values. Kinematic analysis is based on the Mark-land Test Plot method as described by [22, 23] and later modified by [24]. This method was used to assess the potential mechanism i.e., toppling, planar, or wedge sliding along the identified discontinuities (joints). Accordingly, a planar failure is possible when the dip direction of the sliding plane is within ± 20° of the dip direction of the slope face and angle of sliding plane is less than the slope angle but greater than the friction angle along that plane. A wedge failure may occur

Table 2 Orientation (dip/dip dir) of the main discontinuity (joint) sets obtained stereographically, their average/minimum spacings their average characteristics and ratings used in the calculation of the basic RMR rating for investigated slope rock masses in and around Taiz city, Yemen

Station no.			5	22	30	36	41	50	57
Zone			I	I	I	I	I	I-2	I
Zone thickness (m)			6.8	4.2	3.6	2.1->7	>10	1-1.4	1.6->7
Orientation (dip/dip dir) and Average Spacing (m) of Discontinuities	Main Joint Sets	Set1 (J1)	80/036	80/335	82/281	75/265	40/209*	87/074	82/051
			(0.44)	(0.32)	(0.69)	(1.54)	(0.18)	(0.25)	(0.39)
		Set2 (J2)	82/144	41/157	76/109	86/191	82/131	34/185	25/108*
			(0.51)	(0.42)	(0.89)	(1.45)	(0.27)	(0.18)	(1.72)
		Set3 (J3)	15/257*	10/089*	81/023	77/134	82/303	84/354	75/144
			(1.8)	(0.73)	(0.76)	(1.24)	(0.21)	(0.35)	(0.70)
		Set4 (J4)	-	-	23/170*	88/004	-	-	-
			-	-	(2.13)	(1.45)	-	-	-
	Set 4/5 (random)		5/2=2.5	5/3=1.67	5/1=5	5/3=1.67	5/4=1.25	5/1=5	-
	Min. Spacing		0.44	0.32	0.69	1.24	0.18	0.18	0.39
Ground water condition			C.dry	C.dry	C.dry	C. dry	C. dry	C.dry	C. dry
Discontinuities Condition and ratings (as average)	Persistence (m)		<1-10	1-3	<1-3	<1-3	>1	<1	<1-3
	[Rating]		[4]	[4]	[5]	[5]	[6]	[6]	[5]
	Aperture (mm)		1-5	>5	>5	1-5	None	1-5	>5
	[Rating]		[1]	[0]	[0]	[1]	[6]	[1]	[0]
	Roughness		Sm–Sr	Rough	Smooth	Rough	Sm -Sr	Smooth	Sm -Sr
	[Rating]		[2]	[5]	[1]	[5]	[2]	[1]	[2]
	Infilling		No	Hd >5mm	Sf. > 5mm	Sf.<5mm	No	Hd < 5mm	No
	[Rating]		[6]	[2]	[0]	[2]	[6]	[4]	[6]
	Weathering		Slightly	Md	Md	Fresh	Slightly	Md	Slightly
	[Rating]		[5]	[3]	[3]	[6]	[5]	[3]	[5]

Table 2 continued

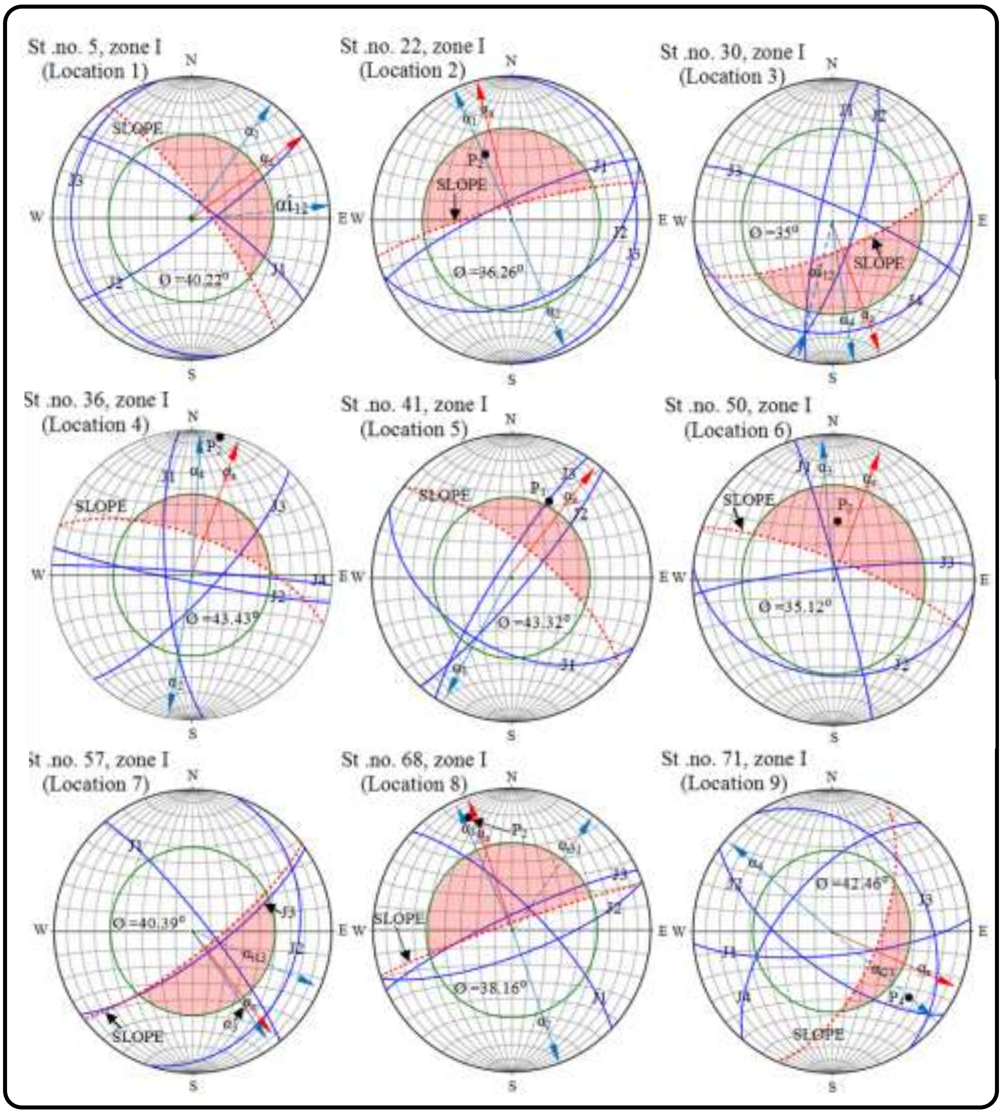
Station no.			68	71	76	77	86	92	96
Zone			I	I	I	I	I	II	I
Zone thickness (m)			1.9	>7	38	6.4	6.5	>7	4.4
Orientation (dip/dip dir) and Average Spacing (m) of Discontinuities	Main Joint Sets	Set1 (J1)	74/044	76/175	55/047	63/213	26/173	40/104	83/275
			(0.36)	(0.22)	(0.24)	(0.22)	(0.13)	(0.10)	(0.31)
		Set2 (J2)	75/160	68/216	62/218	47/342	81/008	81/296	79/015
			(0.33)	(0.38)	(0.28)	(0.33)	(0.26)	(0.12)	(0.79)
		Set3 (J3)	82/335	32/056	77/113	84/091)	41/244	11/222	65/067
			(2.1)	(0.73)	(0.60)	(0.16)	(0.23)	(0.14)	(0.29)
		Set4 (J4)	-	60/310	69/312	-	-	-	-
			-	(0.24)	(0.54)	-	-	-	-
	Set 4/5 (random)		5/1=5	5/3=1.67	5/2=2.5	5/4=1.25	5/4=1.25	5/3=1.67	5/3=1.67
	Min. Spacing		0.33	0.22	0.24	0.16	0.13	0.10	0.29
Ground water condition			C. dry	C. dry	Dry	Dry	Dry	C.dry	C.dry
Discontinuities Condition and ratings (as average)	Persistence (m)		1-3	1-3	<1->20	<1-3	<1	<1	1-3
	[Rating]		[4]	[4]	[3]	[5]	[6]	[6]	[4]
	Aperture (mm)		1-3	< 0.1-1	>5	>5	>5	None	None
	[Rating]		[1]	[4.5]	[0]	[0]	[0]	[6]	[6]
	Roughness		Rough	Rough	S. rough	Smooth	Smooth	Smooth	Sm -Sr
	[Rating]		[5]	[5]	[3]	[1]	[1]	[1]	[2]
	Infilling		Sf. < 5mm	Hd < 5mm	Sf.< 5mm	Hd <5mm	Sf.< 5mm	Hd<5mm	Hd<5mm
	[Rating]		[2]	[4]	[2]	[4]	[2]	[4]	[4]
	Weathering		Slightly	Fresh	Slightly	Md-Hw	Md	Slightly	Fresh
	[Rating]		[5]	[6]	[5]	[2]	[3]	[5]	[6]

Where m: meter, mm: millimeter, (…): the values in parentheses represent the mean discontinuity set spacings, Min: minimum, *: contact between two zones, C.dry: completely dry, S: slightly, Sr: slightly rough, Sf.: Soft, Hd.: hard, Sm.: smooth, Md: moderately/medium, V.: very, [ ]: rating of a parameter according to Beniawski [9], Rr: roughness rating.

Table 3 Orientation (dip/dip dir) of the main discontinuity (joint) sets and slope faces of 14 rock slope stations

Slope St. No. (Location No.)	Zone	Slope Part	Rock Type	Orientation (Dip/Dip dir.) (deg.)(as average)					Remarks about Discont. / Joint set
				Slope Face* (βs /αs)	Main Discont. /Joint set				
					J1 (βj1 /αj1)	J2 (βj2 /αj2)	J3 (βj3 /αj3)	J4 (βj4 /αj4)	
5 (1)	I	Middle	Co-ignimbrite	80/053	80/036	82/144	(15/257)	-	From Table 2
22 (2)	I	Upper	Co-basalt	82/345	80/335	41/157	(10/089)	-	
30 (3)	I	Upper	Rhyolitic tuff	73/158	82/281	76/109	81/023	(23/170)	
36 (4)	I	Upper	Massive rhyolite	68/020	75/265	86/191	77/134	88/004	
41 (5)	I	Upper	J. rhyolite /dacite	71/039	(40/209)	82/131	82/303	-	
50 (6)	I-2	Middle	J. basalt	79/021	87/74	34/185	84/354	-	
57 (7)	I	Upper	Co. rhyolite	78/142	82/051	(25/108)	75/144	-	
68 (8)	I	Upper	J. rhyolite	86/341	74/044	75/160	82/335	-	
71 (9)	I	Full	J. rhyolite	62/113	76/175	68/216	32/056	60/310	
76 (10)	I	Full	Granite	64/053	55/047	62/218	77/113	69/312	
77 (11)	I	Full	Granite	81/029	63/213	47/342	84/091	-	
86 (12)	I	Full	Granite	85/012	26/173	81/008	41/244	-	
92 (13)	II	Full	J. basalt	83/284	40/104	81/296	11/222	-	
96 (14)	I	Middle	Co- basalt	84/281	38/275	79/015	65/067	-	

Where J: Jointed; Co: columnar; Dir.: Direction; deg.: degree; Discont: discontinuity; J1=Joint set1; J2: Joint set2 and so on, *: obtained from filed measurements, the values in parentheses refer to contact between two zones, βj and αj: dip and dip direction of the main discontinuity (joint) set respectively, βs and αs: dip and dip direction of the slope face respectively.



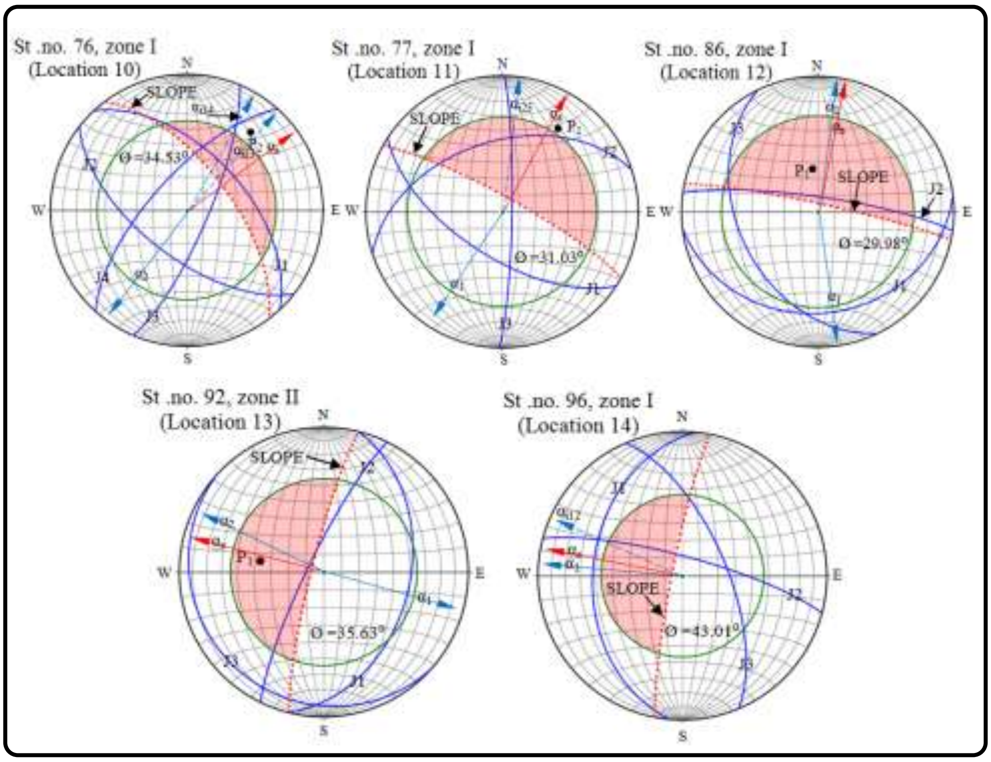


Fig.4 Plot of main joints and slope faces for fourteen rock slope locations. The pink coloured area indicates the critical zone of failure. The symbols used in the figure are: J1=Joint set1, J2= Joint set2,…and J4= Joint set4; αs: dip direction of slope face, α1,2,…4: dip direction of J1, J2,….J4; βi, αi are plunge and trend of line of intersection of two joints respectively; βi12, αi12 are plunge and trend of line of intersection of two joints J1 (joint set1) and J2 (joint set2) respectively so on; Ø: friction angle of the rock mass in degree, P1…4 : pole of the plane 1, 2…4.

when the trend (dip direction) of the line of intersection (αi) is within ± 20° of the dip direction of the slope face, the plunge (dip angle) of the line of intersection (βi) is less than the dip angle of the slope face (βs) (daylights on slope) but greater than the angle of friction of the failure plane (Øj). The kinematic feasibility criterion for toppling failures was formulated as detailed [25]: [(90° − βs) + Øj < βj], where βs is the dip angle of the slope face, Øj is the friction angle of the joint plane and βj is the dip angle of the joint plane.

Based on the average spacing of each main discontinuity (joint) set, the volumetric joint count (Jv) defined as sum of the number of joints per cubic meter (unit volume) [26a, b, 27] was calculated using the following equation [26a]:

$$Jv = 1/S1 + 1/S2 + ... + 1/Sn + Nr/(5\sqrt{A}) \quad (1)$$

where S1, S2 and S3 are the average spacings for the joint sets, Nr is the number of random joints in the actual location and A is the area in m². The spacing of 5m for each random joint was taken as suggested by [26a]. Based on Jv values obtained from Eq. 1, the Rock Quality Designation (RQD, %) index values were estimated using the following equation [28] (Table 4):

$$RQD\ (\%) = 110 - 2.5\ Jv \quad (2)$$

where RQD = 0 for Jv > 44, and RQD = 100 for Jv < 4.

Slopes at fourteen locations were studied and classified for their rock mass quality. The basic Rock Mass Rating (RMR_{b89}) system was calculated by adding rating values for the following five parameters and according to the procedures proposed by Bieniawski [9] (Eq. 3) (Table 5):

1) Strength of intact rock material (A1), 2) RQD (A2), 3) Spacing of discontinuities (joints) (A3), 4) Condition of discontinuities (A4), and 5) Water inflow through discontinuities (A5). RMR has a total range of 0 - 100.

$$RMRb\ 89 = A1 + A2 + A3 + A4 + A5 \quad (3)$$

Table 4 Values of Rock Quality Designation (RQD, %) index calculated based on values of Jv (j/m³)

Station no.	5	22	30	36	41	50	57	68	71	76	77	86	92	96
Zone	I	I	I	I	I	I-2	I	I	I	I	I	I	II	I
Zone thickness (m)	6.8	4.2	3.6	2.1-> 7	> 10	1-1.4	1.6->7	1.9	>7	38	6.4	6.5	>7	4.4
Jv (j/m³)	5.19	10.6	4.56	3.44	14.82	13.01	4.57	6.48	13.31	11.66	14.63	16.69	26.08	8.74
RQD %	97.03	83.5	98.6	100 (1)	72.95	77.47	98.56	93.79	76.72	80.86	73.44	68.28	44.81	88.15

Table 5 The five input parameter values and their ratings required in the calculation of the basic RMR for the different rock slope stations in the study area (after [9])

Slope St. No.	Rock Type	Zone	UCS		RQD		Spacing		Condition of disc		G.W condition		RMRb89	Ø (deg.)
			Values	Rating (A1)	Values	Rating (A2)	Values (m)(min.)	Rating (A3)	Values	Rating (A4)	Values (disc.)	Rating (A5)	Rating (C)	
5 (1)	Co-ignimbrite	I	77.60	7.8	97.03	19.4	0.44	10	Discontinuities Condition (as average)	18	C. dry	15	70.2	40.22
22 (2)	Co-basalt	I	75.6	7.7	83.50	16.5	0.32	10		14	C. dry	15	63.2	36.26
30 (3)	Rhyolitic tuff	I	4.02	1.4	98.60	19.6	0.81	15		9	C. dry	15	60	35
36 (4)	M. rhyolite	I	63.71	6.7	100(1)	20	1.24	15		19	C. dry	15	75.7	43.43
41 (5)	J. rhyolite /D.	I	175.44	13.4	72.95	14.1	0.18	8		25	C. dry	15	75.5	43.32
50 (6)	J. basalt	I-2	42.63	4.9	77.47	15.3	0.18	10		15	C. dry	15	60.2	35.12
57 (7)	Co. rhyolite	I	73.51	7.6	98.56	19.8	0.39	10		18	C. dry	15	70.4	40.39
68 (8)	J. rhyolite	I	52.98	5.7	93.79	18.8	0.33	10		17	C. dry	15	66.5	38.16
71 (9)	J. rhyolite	I	111.31	10.3	76.72	15.2	0.22	10		23.5	C. dry	15	74	42.46
76 (10)	Granite	I	47.66	5.4	80.86	15.8	0.24	10		13	C. dry	15	59.2	34.53
77 (11)	Granite	I	31.44	3.8	73.44	14.4	0.16	8		12	C. dry	15	53.2	31.03
86 (12)	Granite	I	18.94	2.8	68.28	13.6	0.13	8		12	C. dry	15	51.4	29.98
92 (13)	J. basalt	II	81.90	8.1	44.81	9	0.10	8		22	C. dry	15	62.1	35.63
96 (14)	Co- basalt	I	118.94	10.7	88.15	17.4	0.29	10		22	C. dry	15	75.1	43.01
Remarks			From lab/field (as ave.)	From Bieniawskis' chart	From Table 4	From Bieniawskis' chart	From Table 3	Bieniawskis' Table, section (A)	From Table 4	Bieniawskis' Table, section (B)	From Table 4	Bieniawskis' Table, section (A)	Based Eq.(3)	Bieniawskis' Table , section (D)

Where: $RMRb_{89}$ = Basic RMR_{89} with no adjusting factor for joint orientation, A1:ratings for the uniaxial compressive strength of the intact material (UCS; MPa), A2: ratings for the Rock Quality Designation (RQD %), A3: ratings for the spacing of discontinuities (minimum spacing, according to Edelbro, [29], A4:ratings for the condition of discontinuities, A5: ratings for the groundwater condition, G.W: Groundwater, C.dry: Completely dry, (disc.): descriptive term, C: Rock mass classes demined from total ratings, RMC: Rock mass class, RMD: Rock mass description according to Bieniawski [9] , (1): RQD = 100 because Jv < 4 Palmstrom [28], J: Jointed; Co: columnar; M.: Massive, D.: Dacite, the number in parentheses refers to number of slope location.

The original slope mass rating (SMR) system proposed by Romana [7] for rock slope engineering is obtained based on RMRb by adding factorial adjustment factors depending on the joint-slope relationship (multiplication of F1, F2 and F3) and the method of excavation (F4).

$$SMR = RMRb\ 89 + (F1 + F2 + F3) + F4 \quad (4),$$

where, RMRb89 is the basic Rock Mass Rating [9] calculated based on equation 3, F1 depends on parallelism between the dip directions of slope face and the joint plane in the cases of a plane or toppling failure [7], and between the dip direction of slope face and the plunge direction of the intersecting line of the two joint planes in the cases of a wedge failure [30]. The F1 values were given by Romana which ranges from 1 to 0.15 (Table 6), F2 represents the dip angle of joint in the planner mode of failure [7] and the plunge of the intersecting line of two discontinuities in the case of a wedge failure [30]. In a sense it is a measure of the probability of sliding. Its value ranges from 1.00 (for joints dipping more than 45º) to 0.15 (for joints dipping less than 20º), F3 reflects the relationship between the slope face and joint dip. This is equal to (βj-βs) for planer failure, (βj+βs) for failure and topping [9] and (βi-βs) for wedge failure [28]; βj = dip of joint, βi = plunge of line of intersection of two discontinuities and βs = dip of slope. The conditions are favourable when slope face and joints are parallel and very unfavourable when the slope dips 10° more than joints (Table 6) and F4 is the adjustment factor for the method of excavation which has been fixed empirically as shown in the Table 7.

Table 6 Correction parameters for SMR (modified from [7] by [30])

Type of failure			Very favourable	Favourable	Normal	Unfavourable	Very unfavourable
P	A=	|αj-αs|	> 30°	30-20°	20-10°	10-5°	< 5°
W		|αi-αs|					
T		|αj-αs-180|					
P/W/T		F1	0.15	0.40	0.70	0.85	1.00
P	B =	| βj |	< 20°	20°-30°	30°-35°	35°- 45°	> 45°
W	B =	| βi|					
P/W		F2	0.15	0.40	0.70	0.85	1.00
T		F2	1.00	----	----	----	----
P	C =	βj-βs	>10°	10°- 0°	0°	0°-(-10°)	<10°
W		βi-βs					
T		βj+βs	<110°	110°-120°	>120°	----	----
P/W/T		F3	0	-6	-25	-50	- 60

P: Planar failure; T: Toppling failure; W: Wedge failure; α j: Dip direction of discontinuity; αi: Plunge direction of line of intersection two discontinuities; αs: slope; βj: Dip of discontinuity; βi: Plunge of line of intersection two discontinuities; βs: Dip of slope.

Table 7 A adjustment ratings for methods of excavation of slopes (after [7])

Excavation Method	Natural slope	Pre-splitting	Smooth blasting	Normal blasting/ Mechanical	Deficient blasting
F4	+15	+10	+8	0	−8

The values of F1, F2, F3, and F4 were added with the basic RMRb value to compute the SMR values using Eq. 4. Based on SMR values, different stability classes of slopes are identified in addition to rock mass description, stability and probability of failure (Table 8). This system also provides field guidelines and recommendations on support methods especially during the preliminary stages of a project (Fig. 5).

In the study area, from the relationship between the slope face and discontinuities, the adjustment ratings for F1, F2, and F3 were determined for each rock slope station (Table 9). Here, the rating of adjustment factor F4 is given as 0 as the rock cut slopes are formed by Normal blasting /Mechanical excavation method except the slope of station No. 22 which is a natural slope (F4= +15) (Table 9).

Table 8 Description of SMR classes (Modified after [7])

Class No.	V		IV		III		II		I	
	Vb	Va	IVb	IVa	IIIb	IIIa	IIb	IIa	Ib	Ia
SMR Value	1-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-91	91-100
	0 - 20		21 - 40		41 - 60		61 - 80		81 - 100	
Description	Very bad		Bad		Normal		Good		Very Good	
Stability	Completely Unstable		Unstable		Partially Stable		Stable		Completely Stable	
Failure	Big Planner or Soil like		Planer or Big Wedges		Some joints or many Wedges		Some Blocks		None	
Failure Probability	0.9		0.6		0.4		0.2		0	
Hazard Probability	VH		H		M		L		VL	

Table 9 Results of slope mass rating (SMR) for fourteen rock slope stations investigated in and around Taiz city, Yemen (modified after Al-Qadhi, 2017)

Slope location No.	Zone	Critical / semi-critical condition(1)	Probable failure mode	Adjustment factors F1 V/R	F2 V/R	F3 V/R	F4 V/R	RMR_b	SMR	Class No.	Stability	Probability type of failure	Sup. SMR*	Sup. Fld
5 (1)	I	J1	P/F	17°/0.70	80°/1	0°/-25	0	70.2	52.7	III a	Partially Stable*	Some joints or many Wedges	1	a1
		J1& J2	W	32°/0.15	75°/1	-5°/-50	0	70.2	62.7	II b	Stable	Some Blocks	6	
22 (2)	I	J1	P	10°/0.85	80°/1	-2°/ -50	+15	63.2	35.7	IVa	Unstable	Planar or Big Wedge	3	a2
		J2	T	08°/0.85	41°/1	123°/-25	+15	63.2	56.95	IIIa	Partially Stable	Some joints or many Wedges	5	
30 (3)	I	J4	P	12°/0.70	23°/0.40	-50°/-60	0	60	43.2	IIIb	Partially Stable*	Some joints or many Wedges	1	a1
		J1& J2	W	36°/0.15	20°/0.40	-53°/-60	0	60	56.4	IIIa	Partially Stable*	Some joints or many Wedges	1	
36 (4)	I	J2	T/F	09°/0.85	86°/1	154°/-25	0	75.7	54.5	IIIa	Partially Stable	Some joints or many Wedges	5	a2
41(5)	I	J1	T/F	10°/0.85	40°/1	111°/-6	0	75.5	70.4	II b	Stable	Some Blocks	6	a2
50 (6)	I-2	J2	T	16°/0.70	34°/1	113°/-6	0	58.2	54	IIIa	Partially Stable*	Some joints or many Wedges	1	a2
		J3	P	28°/0.40	84°/1	5°/-6	0	58.2	55.8	IIIa	Partially Stable	Some joints or many Wedges	5	
57 (7)	I	J3	P	02°/1	75°/1	-3°/ -50	0	70.4	20.4	Va	Completely Unstable	Big Planner or Soil like	1	a1
		J1& J3	W	28°/0.40	73°/1	-5°/-50	0	70.4	50.4	IIIb	Partially Stable	Some joints or many Wedges	4	
68 (8)	I	J3	P/F	06°/0.85	82°/1	- 4°/-50	0	66.5	24	IVb	Unstable	Planar or Big Wedge	2	a4
		J2	T	01°/1	75°/1	161°/-25	0	66.5	41.5	IIIb	Partially Stable	Some joints or many Wedges	4	
		J1& J3	W	55°/0.15	74°/1	-12°/- 60	0	66.5	57.5	IIIa	Partially Stable	Some joints or many Wedges	5	
71 (9)	I	J1& J3	W	21°/0.40	27°/0.40	-25°/-60	0	74	64.4	II b	Stable	Some Blocks	6	a2
		J3	T	57°/0.15	32°/0.70	-30°/-60	0	74	67.7	II b	Stable	Some Blocks	6	
76 (10)	I	J1	P/F	06°/0.85	55°/1	-9°/ -50	0	59.2	16.7	Va	Completely Unstable	Big Planner or Soil like	1	a2
		J2	T	15°/0.70	62°/1	126°/-25	0	59.2	41.7	IIIb	Partially Stable	Some joints or many Wedges	4	
		J3& J4	W1	23°/0.40	28°/0.40	-36°/-60	0	59.2	49.6	IIIb	Partially Stable	Some joints or many Wedges	4	
		J1& J3	W2	11°/0.70	55°/1	-9°/ -50	0	59.2	24.2	IVb	Unstable	Planar or Big Wedge	2	
77 (11)	I	J1	T/F	04°/1	63°/1	144°/-25	0	53.2	28.2	IVb	Unstable	Planar or Big Wedge	2	a6
		J2 & J3	W	22°/0.40	44°/0.85	-37°/-60	0	53.2	32.8	IVa	Unstable	Planar or Big Wedge	3	
86 (12)	I	J2	P/F	04°/1	81°/1	- 4°/ -50	0	51.4	1.40	Vb	Completely Unstable	Big Planner or Soil like	1	a7
		J1	T	19°/0.70	26°/1	111°/-6	0	51.4	47.2	IIIb	Partially Stable	Some joints or many Wedges	3	
92 (13)	II	J2	P	12°/0.70	81°/1	-2°/ -50	0	62.1	27.1	IVb	Unstable	Planar or Big Wedge	2	a2
		J1	T	00°/1	40°/1	123°/-25	0	62.1	37.1	IVa	Unstable	Planar or Big Wedge	3	
96 (14)	I	J1	P	06°/0.85	38°/0.85	- 46°/-60	0	75.1	31.75	IVa	Unstable	Planar or Big Wedge	2	a2
		J1& J2	W	12°/0.70	37°/0.85	- 47°/-60	0	75.1	39.4	IVa	Unstable	Planar or Big Wedge	2	

1. Reexcavation/wall and drainage
2. Reexcavation/wall, drainage/ concrete
3. Drainage / concrete/ reinforcement
4. Concrete (anchors systematic)/ reinforcement (systematic bolting) /protection (Toe wall and/or dental concrete Toe wall)
5. Concrete (spot concrete)/ reinforcement (spot or systematic bolting) /protection (Toe ditch and /or nets)
6. Scaling/none, reinforcement (spot or systematic bolting) protection (Toe ditch or fence, nets)

(a1). Removing all unstable or potentially unstable rock blocks from upper part of the slope (head)
(a2). Removing all unstable or potentially unstable rock blocks from upper part of the slope (head) and erection of gravity retaining wall along with drainage holes at slope toe
(a3). Removing all unstable or potentially unstable rock blocks from upper part of the slope (head) and surface drainage.
(a4). Removing all unstable or potentially unstable rock blocks from upper part of the slope (head) and construction of Toe ditch along slope toe
(a5). None /scaling
(a6). Scaling and trimming and construction of Toe ditch along slope toe.
(a7). Reexcavation of the upper portion of slope and erection of gravity retaining wall along with drainage holes at slope toe

V: Value; R: Rating; P: Planar failure; T: Toppling failure; W: Wedge Failure; F: Fall failure; *: unstable based on the field observations; Sup.: Support; SMR*: suggested remedial measures based on SMR values using Figure (5); Fld: suggested remedial measures based on field observations

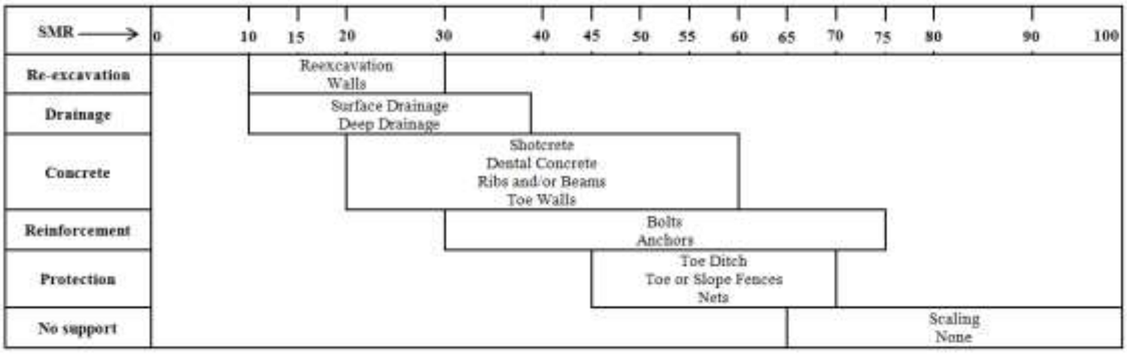


Fig.5 Slope support guidelines based on SMR (after [7])

2.III Laboratory Investigations

Laboratory investigations include the determination of the strength of the intact rock samples (σi; MPa) by Uniaxial Compressive Strength (UCS) test, Point Load Test (PLT) and/or Schmidt Hammer rebound test (SH) (in the field and lab.). The UCS test was carried out on cubic/ prismatic rock samples according to the procedure prescribed by UNIEN 1926 [31]. The PLT test was performed on rock samples of definite geometrical form and also on irregular lumps [32, 33]. The UCS (MPa) obtained from the previous test was based on the relationship between the PLT and UCS [34]. SH test was carried out both in the field and laboratory following the procedures of Barton and Choubey [35] and ISRM [36] using Schmidt Hammer N-type. The data obtained by using N-type Schmidt hammer test was converted to L- type Schmidt hammer data using the empirical equation proposed by Ayday and Grktan [37] and then converted to equivalent UCS (σi; MPa) values using the equation and chart of Miller presented by Dear and Miller [38]. When the tests of unit weight are not conducted or the unit weight value is less than 20 KN/m³, the equation proposed by Dincer et al, [39] was used for the calculation of UCS value. The obtained results of UCS (σi; MPa) from these tests were averaged and used in the calculation of RMRb.

IV. RESULTS AND DISCUSSION

Detailed geological investigations including discontinuities (joints) mapping were made in the study area along fourteen of road cuts, quarries and natural exposures. These rock outcrops constitute different lithologies as well as geotechnical characterristics. The slopes have steep to very steep dip angle with developed systems of discontinuities (joints) (Table 3). Most of the upper zones of these slopes are underlined by volcaniclastic materials and volcanic soils. For each slope, the average orientations of main joint sets and the average orientation of slope face were re-plotted on stereo net for the purpose of the kinematic analysis using friction angle obtained based on RMRb (Table 5). The identified critical zone of failure has been shown in pink colour in stereo-net projection for all fourteen slope locations (Fig. 4). Kinematic analysis indicates mainly planar, toppling and wedge type of failure based on the discontinuity (joint) patterns (Fig. 4 & Table 9). The planar and toppling/fall types of failures are common in all investigated slope locations.

The results of required parameters for RMR classification have been presented in Table 5. The calculation of RMRb has been performed for all fourteen slope locations (Table 5). The range of RMRb values varies from 75.7 to 53.2 belonging to "Good" to "Fair" classes of Bieniawski [8, 9]. The rock masses with rating values of 59.2, 60 and 60.2 may be classified as "Fair" rock, however, the values are very close to the interface between the classes "Fair" and "Good" rocks thus warranting special attention as well as proper care of the slope.

As per the standard classification, the values of SMR at locations 5 (zone-I), 22 (zone-I), 30 (zone-I), 50 (zone-I - 2), 57 (zone-I), 68 (zone-I), 76 (zone-I), 86 (zone-I), 92 (zone-II) and 96 (zone-I) show values 52.7, 35.7, 43.2, 55.8, 20.4, 24, 16.7,1.40, 27.1 and 31.75 for planar (P) failure respectively. Accordingly, the slopes 5 (zone-I), 30 (zone-I) and 50 (zone-I - 2) may be classified in class III (IIIa & IIIb) as partially stable (Moderate Hazard), while the slopes 22 (zone-I), 68 (zone-I), 92 (zone-II) and 96 (zone-I) may be classified in class IV (IVa & IVb) as unstable (High Hazard). The slopes at locations 76 (zone-I) and 86 (zone-I) are classified in class V (Va &Vb) as "Completely Unstable" (Very High Hazard) against planar failure and the probability of failure is 90 %. At location 57 (zone-I), the slope is very close to the boundary between unstable (High Hazard) and completely unstable class (Very High Hazard) against planar failure (Tables 8 & 9).

As noted in slope 5 (zone-I) (Fig. 4), the dip angle of the plane of J1 (βj1°) is almost equal to the dip angle of the slope face (βs°), thus indicating no daylight on slope face and hence no failure. However, the field observation [40] indicates that this part of the slope is "Unstable" (High Hazard) and may cause planar/fall or toppling failure owing to 1) the presence of strong columnar ignimbrite at the top (Fig. 6) (geotechnical properties are: Wc =1.65 %, γ = 24.7 KN/m³, n = 3.97%, W. Ab. =1.6%, UCS = 77.6 MPa, RMR= 70.2, RQD = 97.03% and GSI= 66.25) and 2) presence of underlying layered and fractured ignimbrite [geo-technical characteristics: moderately weathered (in some parts it is highly weathered), Wc = 4.23%, γ = 22.46 KN/m³, UCS = 22.57 MPa and GSI= (40-60)].

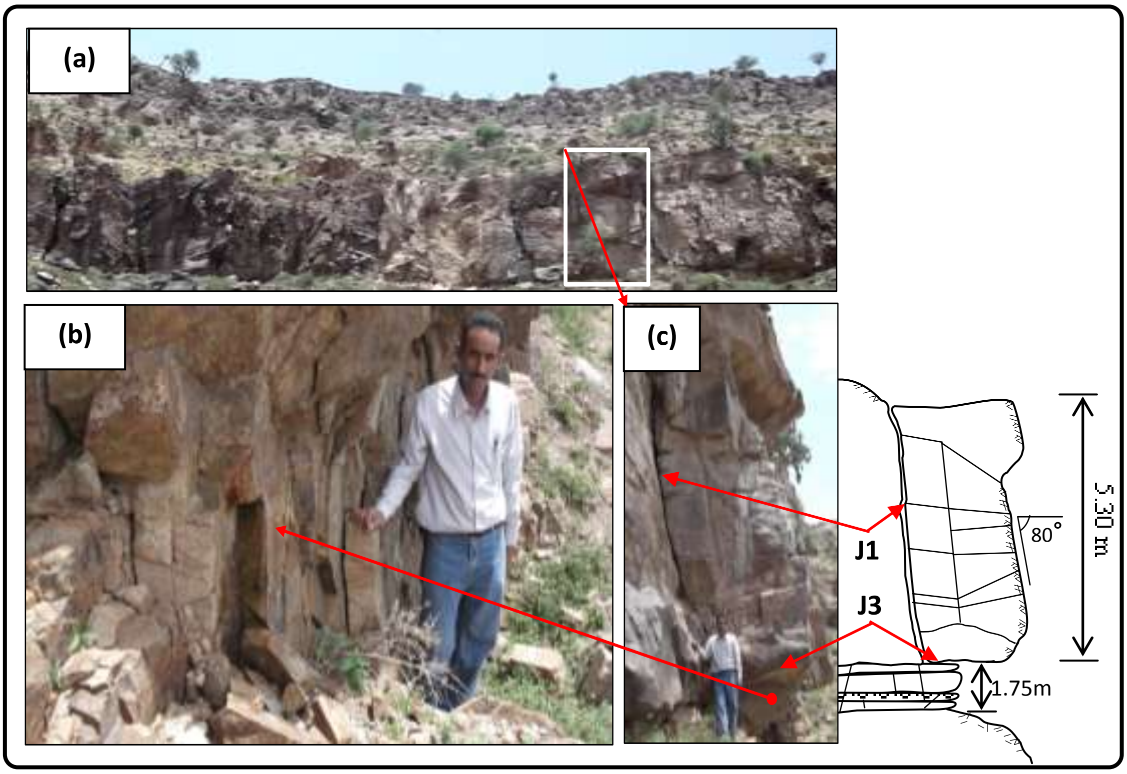


Fig. 6 Field photographs of the rock slope at station.No.5 (zone I); **a)** Front view showing the middle part of the slope made up of ignimbrite rocks with columnar jointing structures **(b)** underlain by weakly fractured, layered ignimbrite rocks; **c)** Note the overhanging blocks not yet fallen in some parts of the slope as well as the build-up of the tensile stress J1 (back release surface) behind the columnar ignimbrite rock block.

The values of SMR at locations 22 (zone-I), 36 (zone-I), 50 (zone-I - 2), 68 (zone-I), 76 (zone-I) and 86 (zone-I) are 56.95, 54.5, 54, 41.5, 41.7 and 47.2 for toppling/fall (T/F) failure respectively, indicating that the rock masses of these slopes are in "Normal and partially stable conditions" (Class No. III; IIIa & IIIb); and the probability of toppling/fall (T/F) failure is 40 % (Moderate Hazard).

At locations 77 (zone-I) and 92 (zone-II) the values of SMR are 28.2 and 37.1for toppling/fall (T/F) failure respectively indicating that these two slopes are unstable (Class-IV; IVa & IVb) (High Hazard). At locations 41 (zone-I) and 71 (zone-I) the slopes are stable (Low Hazard) and in good conditions against toppling/fall (T/F) failure and the probability of failure is 20 % (Tables 8 & 9).

The suggested remedial measures for these slopes based on SMR values (Fig. 5) as well as field observations are provided in Table 9. At location 50 (zone-I-2), the evaluated probable plane failure along J3 and toppling failure along J2 (Fig.4) indicated that the rock slope in this site is "Normal and in partially stable condition" (Class. No. III; IIIa) (Table 9); however, that the field observations indicate the failure of some rock blocks possibly due to tension cracks which may have been developed as a result of differential settlement of jointed basalt and basic volcaniclastic rocks underlain by weak volcaniclastic deposits (volcanic soil). In addition, the latter deposits in the lower part of the slope are highly weathered and eroded, leading to active undercutting that left some parts of the slope overhanging.

As per the standard classification, the values of SMR at location 76 (zone-I) show the values of W1 and W2 as 49.6 and 24.2 respectively. The obtained values suggest that the slope is "Partially Stable" (Moderate Hazard) in case of wedge failure W1 (Class-III; IIIb) but "Unstable" (High Hazard) for wedge failure W2 (Class-IV; IVb).

The values of SMR at locations 30 (zone-I), 57 (zone-I) and 68 (zone-I) are 56.4, 50.4 and 57.5 for wedge failure (W) respectively. The values suggest that the slopes belong to class III (IIIa

&IIIb) which are "Partially Stable" (Moderate Hazard). The values of SMR at locations 77 (zone-I) and 96 (zone-I) are 32.8 and 39.4 for wedge failure (W) respectively. These slopes fall in the category of class IV (IVa & IVb) which are "Unstable" and in bad conditions and the probability of failure is 60 % (High Hazard) (Tables 8 and 9).

According to the obtained Slope Mass Rating (SMR) values (Table 9), rock mass of station No.30 (zone I) is in "Normal and partially stable condition" (Class No. III; IIIa & IIIb) against wedge and planner failures; however, the failure of this slope took place in the field. The landside witnessed along this slope may probably has been triggered by rainfall causing differential settlement in jointed rhyolitic tuff emplaced on weakly volcaniclastic deposits (volcanic soils) (Fig.7). The geotechnical properties of jointed rhyolitic tuff and volcaniclastic deposits [40] respectively are: [Wc = 0.4 %, ρd (ave.) = 2.05 gm/cm³, n= 21.79 %, W. Ab. =10.57%, UCS (ave.) = 4.02 MPa, RMR= 60 and GSI= 41.2)] and (Wc = 2.21%, ρd= 1.65 gm/m³, Gs = 2.52, LL=51.94 %, PL= 26.04 % = 4.02 and PI= 25.90%).

Table10 and Fig. 8 show the various stabilities and modes of failure in the investigated rock slopes presented for the different lithological conditions. Generally, the slopes classified as partially stable, unstable and completely unstable need remedial measures to support them or to prevent a believed potential instability (Table 9).

V. FACTORS THAT CONTRIBUTE TO SLOPE INSTABILITY IN THE STUDY AREA

Detailed studies at the above discussed fourteen locations brought to light different geo-engineering conditions and have revealed that both natural and anthropogenic factors are responsible for the slope failures.

1. V Natural Causes:

1.1.V Structural Factors: All geological units in the study area are affected by different types of joints (discontinuities) having different orientations. This led to slope instability due to the following:

i) Increasing probability of failure along joints which created mechanically preferential paths through which failure is initiated. ii) Presence of more than one type of failure modes (Planner, wedge, toppling, fall, etc.), even within the same slope. iii) Open joints developed in the volcanic rock masses tend to weaken the strength of the rocks and increase their permeability, especially during rainfall periods. iv), Variation in the sizes and shapes of the detached rock blocks. v) Discontinuities corresponding to contact surface between different lithologies have aided in the determination of the height of the detached rock blocks and in this way has influenced the stability of a number of slopes. vi) Joint sets in almost half of the slope stations have high dips (70°-90°). This set up act as back release and lateral release surfaces or composite back release during sliding process. This means that the presence of inclined discontinuities led to the daylighting of some the discontinuity planes of the blocks triggering sliding type of failure.

2.1.V Lithological Factors: The following are the lithological factors which may have contributed for the instability of the slopes:

i) Most part of the study area is covered by Tertiary volcanic rocks and associated intrusive bodies. The Tertiary volcanic rocks consist of basalt/ rhyolite volcanic lava flows (bimodal) and varicoloured weakly welded volcaniclastic materials (ignimbrites, tuffs, volcaniclastic breccias, volcaniclastic agglomerates, volcanic ashes /soils) of basaltic/rhyolitic composition. ii)The presence of weakly welded basaltic/rhyolitic volcaniclastic zones at the lower part of the slope, with effects of differential erosion and /or human activities (excavation) resulted in the development of overhanging in some parts of the slope. The latter led to the slope/block failure causing rock fall and secondary toppling as well as differential settlements in foundations constructed on them. ii)The presence of clay minerals in weakly welded volcaniclastic zones at the lower part of the slope, with effects of differential erosion and /or human activities, led to form overhanging in some parts of the slope, which caused slope/block failure by rock fall and secondary toppling. iii) Alternating layers of different lithologies (very hard jointed lavas such as basalts/rhyolites with weak volcaniclastic deposits) may cause the differential settlements in foundations constructed on them. iv) Volcaniclastic deposits are characterized by diversity in their types, textural features, thicknesses, grain sizes, matrix materials, and degree of roundness of rock fragments and alternating and/or interlocking as well as intercalation laterally and vertically with basalt/rhyolite lava rocks. This variation has a great bearing on the stability of the slopes. v) In Tertiary Sabir granitic rock masses, some slopes consist of hard granitic zones and are underlain by intensively weathered granitic bodies as seen in the slope of station No. 86 which led to overhanging in some parts of the slope and development of tension cracks.

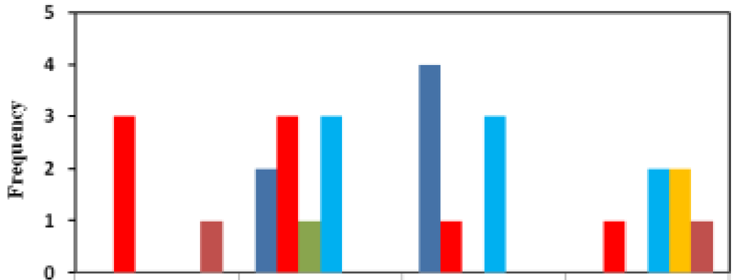
3.1.V Geotechnical Factors: i) The upper hard jointed lava flows which overlie the weak lower volcaniclastic materials are dense and are characterized by open discontinuities especially the vertical joints which can induce instability and infiltration of water into the lower zones during rainfall periods.

Fig. 7 Field photograph of the slope of station No.30 (zone-I) showing two different lithologies of the slope. Note the unstable columnar blocks in the upper part as well as the detached rhyolitic tuff blocks settled at the toe of the slope

Table 10 Various stabilities and mode of failure in the rock slopes presented in the different lithologies conditions

Stability	Mode of failure		
	Planar	Toppling/Falling	Wedge
Stable	-	41^{2},71^{2}	5^{5},71^{2}
Partially Stable	50^{1}	22^{1}, 36^{3}, 68^{2}, 76^{6},86^{6}	57^{2}, 68^{2},76^{6}
Unstable	22^{1} , 68^{2},92^{1}, 96^{1}	77^{6},92^{1}	76^{6},77^{6},96^{1}
Completely Unstable	$5^{5,*}$, $30^{4,*}$, 57^{2},76^{6}, 86^{6}	$50^{1,*}$	$30^{4,*}$

[1]: Jointed/columnar basalt; [2]: Jointed/columnar rhyolite; [3]: Massive rhyolite; [4]: Rhyolitic tuff; [5]: Ignimbrite; [6]: Granite, *: based on geotechnical properties and field observation.



	Stable	Partially Stable	Unstable	Completely Unstable
Jointed/columnar basalt	0	2	4	0
Jointed/columnar rhyolite/dacite	3	3	1	1
Massive rhyolite	0	1	0	0
Granite	0	3	3	2
Rhyolitic tuff	0	0	0	2
Ignimbrite	1	0	0	1

Fig. 8 Classification of the rock types of the investigated slope regions in the study area according to their stability (after [40])

ii) The lower volcaniclastic deposits are characterized by low strengths, low densities, high porosities, high plasticity, medium to very high degree of expansiveness (in case of soils). At places, these materials are also affected by the discontinuities [4]. iii) Buildings in Taiz city and its surroundings, that have come up on the well jointed lava flows have also become vulnerable for all kinds of damages. This may be attributed to the collapse of high-density upper hard jointed lava flows due to erosion and removal of the underlain weak volcaniclastics and the presence of expansive volcanic soils. This can be noticed along the slope regions of the study area which bear imprints of overhanging of upper jointed lava. iv) The volcanic soils made up of clay minerals such as montmorillonite and kaolinite are very sensitive to wet conditions and rainfall. They are prone to rapid increase of the pore pressure and decrease of shear strength, leading to slope stability problems.

4.1.V Geomorphological Factors

In some locations, the Tertiary volcanic lava flows are overhanging due to the undercutting of the slope made up of weak volcaniclastic materials by weathering/human activities. Further, the upper part of the slopes is affected by different types of joints (discontinuity) having various orientations. Several slope regions at their upper part show toppling or fall and planer failures (e.g., near the AL-Thawrah hospital and Al-Sha'ab palace).

5.1.V Hydrological Factors

The study area is characterized by an arid to semi-arid climatic condition. The average annual rainfall in the study area is about 520 mm. Rainfall is the main triggering factor which cause slope instability and increase in the incidence of landslides. The inventory of landslides in the study area indicates that a majority of the landslide incidences have occurred during or after significant rainfall. During the rainfall periods the meteoric water might have caused the slope instability as a consequence to one or more of the following processes: i) Higher rate of infiltration of water into lower weak volcaniclastic zones overlain by jointed volcanic rocks can induce instability in the entire of the sequence and consequently, the buildings that have come up on them have become vulnerable to all kinds of damages. ii) Higher rate of differential erosion of the exposed lower weak volcaniclastic zones. iii) Higher flow rate of surface water through stream channels and Wadis erode the lower portions of the slopes thereby reducing the mass at the toe of the slopes which in turn reduces the resisting forces causing instability. iv) Absorption of water by the volcanic soil and subsequent drying of the same leads to alternating swelling and drying of the clay minerals, which in turn causes slope instability.

2. V Anthropogenic Causes

1. Human activities such as excavations for construction purposes, road building and loading of the upper slope or crest regions etc., cause changes in the stability of the slope at its toe region (e.g., Jabal Amid, Al-Jabal Al-Mahjoor, Al-Massbah area, etc).

2. Random construction of housings at the top of the slope form additional load on slope body and increase the gravitational forces that cause failure for number of slopes and housing foundations. Also sewage chambers constructed in slope bodies, increase water pressure along the surfaces of discontinuities and reduce cohesion between those surfaces due to leakage of sewage water into lower weak volcaniclastic deposits zone through the discontinuities present in the rock masses of the upper zone of slopes. In lower zone the water saturated pore spaces will also support the weight of overlying material thus reducing the effect of friction. Finally, the addition of water may promote instability by adding weight to a slope.
3. Use of explosives during excavation of foundations on toe of slopes increases failure for slopes and damage to housing constructed on them.

VI. CONCLUSION

The present work of slope stability assessment, centers around 14 vulnerable slope stations selected from 110 investigated field stations in Taiz city of Yemen. The chosen stations are representtative of the various geo-engineering conditions existing in the study area. Evaluation of the stability of the slopes was carried out by applying original Slope Mass Rating (SMR) and Kinematic analysis techniques. The SMR study of the investigated rock slope stations indicates that the rock masses of these stations have various stabilities even within a single slope. The values of the evaluated geotechnical parameters fall from "Stable" (II-class) (Low Hazard) to "Completely Unstable" (V-class) (Very High Hazard) classes with probability of failure ranging from 0.2 to 0.9. The slopes are vulnerable for more than one mode of failure (planar/falling, toppling/falling, wedge) even along a single slope depending on joint patterns and their orientations, their relationship with slope faces as well as friction angle on the surface of discontinuities and the geological condition of the rocks of slopes. Most of the "Unstable" and "Completely Unstable" slopes showing different modes of failure (planar, toppling/ falling, wedge) are located in the slopes made up of jointed/columnar basalts, Sabir granitic rocks and rhyolitic tuff. The slopes belonging to "Stable", "Partially Stable","Unstable" and "Completely Unstable" classes form 14 %, 31%, 31% and 24 % respectively of the examined critical sections using SMR system and confirmed by kinematic analysis. Based on this study, the factors that play a significant role in controlling the conditions of slope instability in the studied area can be categorized into two main groups: I. Causal factors - include 1) Geological factors (type of rock, mode of its emplacement, strength of intact rock, strength along surface of discontinuities, presence of weakly welded volcaniclastic materials and presence of different discontinuities with unfavourable orientation); 2) Morphological factors (slope forms and the processes that shape them) and 3) Hydrological factors (movement, distribution, drainage and infiltration). II. Triggering factors include: 1) Rainfall; 2) Weathering especially of granitic rocks and weakly welded volcaniclastic materials; 3) Human activities (excavation of the slope in the toe region for the purpose of constructions of building, laying road, loading of the upper slope or crest regions, etc); 4) Undercutting (weathering/human activities); 5) Or a combination of all of the above factors. Based on the results of the present study, the investigators recommend that for the application of SMR system in the areas of excavated slopes located in the complicated volcanic environments, special attention as well as proper care is required.

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