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Slope Stability Evaluation of Gneiss Rock Slopes Using SMR and QSlope

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Abstract

- One of the biggest problems in open pit mining is slope stability. The avoidance of slope stability problems depends on a comprehensive assessment of environmental and operational factors such as geology, climate and mining activities. In the light of these considerations, slope geometries should be determined in accordance with engineering principles. In this research, the slope stability of rock slopes in a mine opened in gneiss geological unit has been studied. Production activities were stopped in 2019 due to the slope movements in the eastern part of the quarry. In order to continue the production safely, field works have been carried out primarily. To assess slope stability, detailed discontinuity surveys were carried out on bench faces. Subsequently, kinematic and numerical analyses were employed to identify geometries that are expected to maintain stability under the prevailing geological structures and environmental constraints. Engineering geological studies such as scanline measurements in steps and investigation of potential failure mechanisms by kinematic analysis technique were carried out. SMR and Qslope, rock mass classification systems were used to evaluate slope stability. Based on these classification systems potential unstable rock slopes were determined and thematic maps were created using geographic information systems (GIS). The most suitable slope geometries are suggested for these slopes. In addition, the improvement methods suggested by the rock mass classification systems were proposed for these slopes.

Keywords: Gneiss, QSlope, Slope Mass Rating (SMR), Rock Mass Classification Systems, Slope Stability, Open Pit Mine

Introduction

- Although there are many definitions of slope it can be generally defined as "the mass that makes a certain angle with the earth's face" (Cernica, 1995; Das, 1994). Slope failures usually cause great loss of property and lives. Therefore, engineers have to determine and evaluate the stability of slopes (Coduto, 1999).
- Mass movements dominantly occur as a result of gravitational forces acting on slope. However, there may be one or more reasons that accelerate the occurrence of these movements. These can be divided into internal and external causes. External causes include "excavations on the toe of the slope changing the angle of the slope, removing the overburden of the slope and facilitating the entry of surface waters into the slope", while internal causes include "increase in pore water pressure (u), decrease in cohesion of the slope material and decrease in the internal friction angle" (Kılıç, 2005).
- For safe slope design geological conditions should be considered. Therefore, different slope designs around the mine may be required. It is the determination of the maximum slope height and slope angle planned for rock slopes. In the first stage of design, there is a balance between slope stability and economy. It means that the volume of rock required to be excavated is less and steeper slopes have a lower cost than slopes with less slopes (Hoek and Bray, 2004).

- In this study, slopes of an open pit mine opened in gneiss is considered for the reasons stated above. There are many different mining enterprises large and small in this area of study and slope movements are common in this area. Field investigations, engineering geological works and rock slope stability assessments were carried out within the scope of this study in order to stabilize the rock slopes opened in gneiss and to continue operations. The stability of the slopes was determined with the measurements made in the summer months of 2020. With the help of these studies, the determination of unstable slopes and the improvement and/or reinforcement processes of these slopes were determined in order to continue the production in a healthy and efficient way. However, the steepest slope angles that can remain stable without any reinforcement and improvement are revealed. In addition, a digitising process was carried out using geographic information systems in order to evaluate these slopes, to identify the slopes that may failure and to better understand the classification systems that were used.

Geological Setting

- The study area is located in the Menderes Massif, which constitutes one of the main tectonic zones of Anatolides that crop out in Western Anatolia (Graciansky, 1965). There are eighteen albite open pits of different sizes in this region. The studied mine is one of the most famous albite mining sites in the region (Kıncal, 2014). Leucocratic orthogneisses rich in terms of tourmaline were exposed in the study area. Two types of tourmaline-rich leucocratic orthogneisses were detected in the study area. The first group consists of orthogneisses derived from granoblastic textured coarse granites. The foliation planes of these rocks are defined by the parallel sequence of muscovites. This condition type consists of medium-grained, albite-rich leucocratic orthogneisses (Candan et al., 2005). All of the geological units in the open pit albite mine have been deformed by a shear zone. The Na-feldspar ore-bearing zone with mineralogical composition was developed along the shear zone. The dip directions of foliation planes in orthogneisses are almost perpendicular to this zone. Orthogneisses are characterized by their massive structures. It is seen that the mine site contains gneiss as ore body and wall rock (Figure 1). The direction of the ore deposit is N27E/55-60SE with an approximate length of 660 m developing along the shear zone in the mine. Metaquartzite and rutile lenses are observed. These lenses tend in the NE-SW direction.

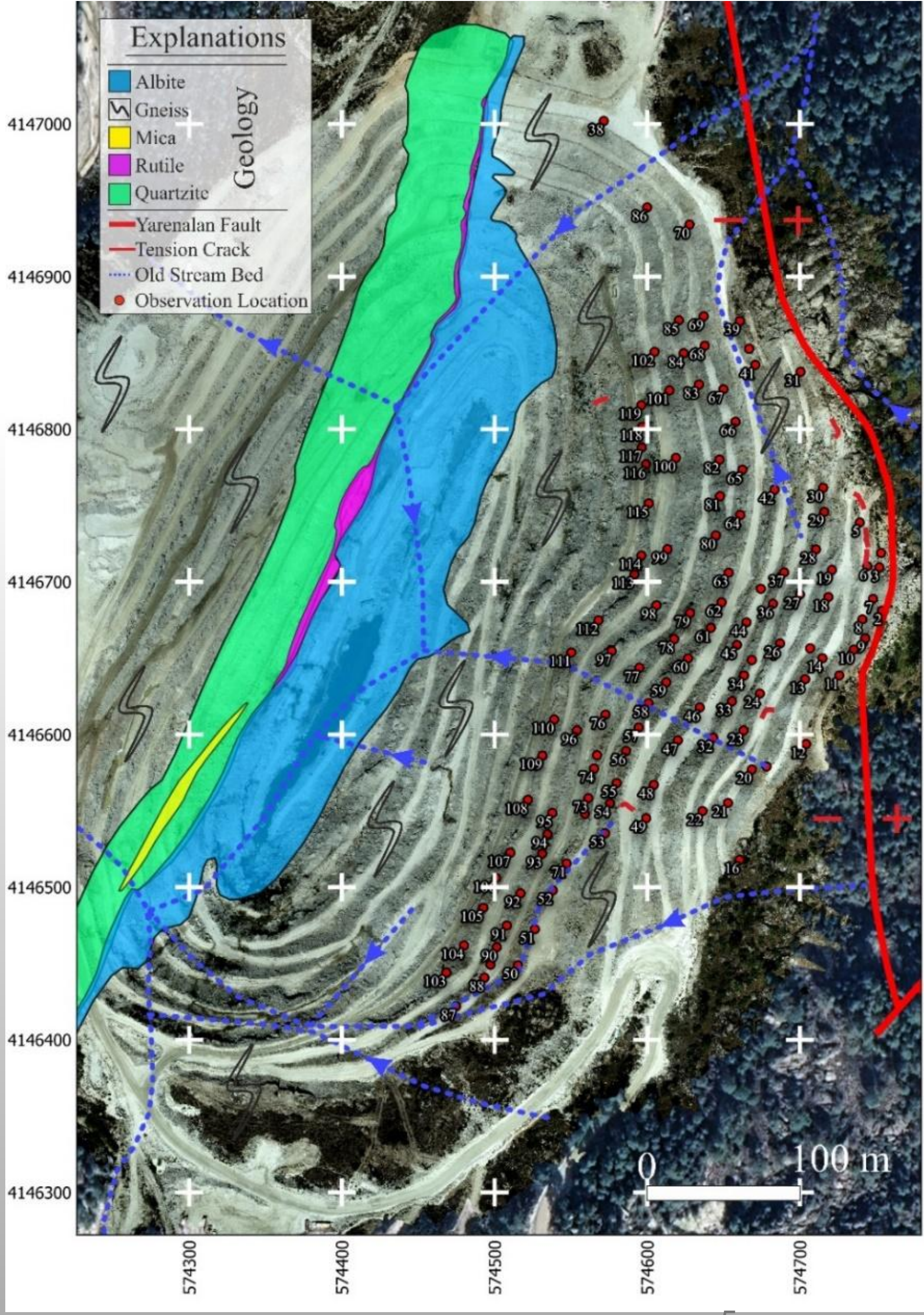

Figure 1—Engineering geological map of the study field (The red line is given as Yarenalan

Engineering Geology

- Rock slopes often failure along existing geological structures. Therefore, most slope problems require consideration of geometric relationships among discontinuity planes, slope, and related force vectors. One of the most important requirements for rock slopes is to determine the correct failure mechanism (Bell, 1992). Within the scope of this study, scan-line works proposed by ISRM (2007) was conducted at 119 different observation points in the eastern part of the open pit mine opened in gneisses (Figure 1).
- 1613 discontinuity measurements were recorded from these observation points and the data (such as orientation of discontinuity spacing, persistence, roughness, etc) were evaluated according to ISRM (2007) standards. The orientations of the discontinuity planes were transferred to the stereographic projection with Dips 7.016 (RocScience, 2019) software and the type of failures at each observation point were evaluated kinematically and expressed as a percentage in the Table I. In addition, the major discontinuity sets in the open pit mine slopes were determined by using the pole concentration points of all discontinuities taken from the eastern part of the mine (Figure 2). In addition, the classes and properties of the dominant discontinuity sets recommended by ISRM (2007) are given in Table II.

Table I. Type of failures kinematically at observation points

W	Wedge (44) (%58)
P	Planar (10) (%13)
T	Toppling (22) (%29)

Location	Slope dip/dip direction	Potential Failure Type	Potential of failure mechanism	Location	Slope dip/dip direction	Potential Failure Type	Potential of failure mechanism	Location	Slope dip/dip direction	Potential Failure Type	Potential of failure mechanism	Location	Slope dip/dip direction	Potential Failure Type	Potential of failure mechanism
1	38/284	Kinematically Stable	-	31	44/245	W	S.C.	61	73/297	W	S.C.	91	47/292	P	S.C.
2	38/286	Kinematically Stable	-	32	55/290	W	S.C.	62	55/285	T	S.C.	92	54/289	W	S.C.
3	43/272	Kinematically Stable	-	33	50/295	W	S.C.	63	45/278	W	S.C.	93	60/308	P	S.C.
4	39/275	Kinematically Stable	-	34	57/295	P	S.C.	64		Kinematically Stable	-	94	52/285	W	S.C.
5	40/267	Kinematically Stable	-	35	58/290	Kinematically Stable	-	65		Kinematically Stable	-	95	45/282	W	S.C.
6	41/274	T	S.C.	36	58/296	W	S.C.	66		Kinematically Stable	-	96	56/286	T	S.C.
7	48/285	Kinematically Stable	-	37	58/288	W	S.C.	67		Kinematically Stable	-	97	55/315	W	S.C.
8	58/281	W	S.C.	38	50/190	Kinematically Stable	-	68	44/257	W	S.C.	98	55/298	W	S.C.
9	56/273	Kinematically Stable	-	39	74/248	T	S.C.	69		Kinematically Stable	-	99	60/285	T	S.C.
10	56/270	T	S.C.	40	60/243	Kinematically Stable	-	70	39/231	W	S.C.	100		Kinematically Stable	-
11	48/309	P	S.C.	41	54/253	T	S.C.	71	81/304	T	S.C.	101		Kinematically Stable	-
12	47/277	Kinematically Stable	-	42		Kinematically Stable	-	72		Kinematically Stable	-	102	48/268	Kinematically Stable	-
13	50/291	T	S.C.	43	54/296	T	S.C.	73	51/288	W	S.C.	103	45/315	W	S.C.
14	48/286	P	S.C.	44	73/294	W	S.C.	74	55/288	W	S.C.	104		Kinematically Stable	-
15		Kinematically Stable	-	45	59/300	Kinematically Stable	-	75	63/294	W	S.C.	105	54/298	W	S.C.
16		Kinematically Stable	-	46	47/301	T	S.C.	76	38/290	Kinematically Stable	-	106		Kinematically Stable	-
17		Kinematically Stable	-	47	35/310	Kinematically Stable	-	77		Kinematically Stable	-	107	63/293	T	S.C.
18	48/279	W	S.C.	48	40/299	W	S.C.	78	57/308	W	S.C.	108	60/278	P	S.C.
19	48/298	Kinematically Stable	-	49	44/282	P	S.C.	79	60/291	W	S.C.	109	60/285	T	S.C.
20	45/286	W	S.C.	50	47/282	T	S.C.	80	50/284	T	S.C.	110	60/276	W	S.C.
21	47/288	T	S.C.	51	51/287	W	S.C.	81	48/276	W	S.C.	111		Kinematically Stable	-
22	38/298	Kinematically Stable	-	52	53/295	W	S.C.	82	50/261	W	S.C.	112	58/310	W	S.C.
23	62/297	Kinematically Stable	-	53	43/278	W	S.C.	83	45/260	T	S.C.	113	50/286	Kinematically Stable	-
24	59/296	Kinematically Stable	-	54		-	-	84		Kinematically Stable	-	114		P	S.C.
25	59/295	P	S.C.	55	45/296	T	S.C.	85	42/270	W	S.C.	115	68/272	W	S.C.
26	62/287	Kinematically Stable	-	56	41/302	W	S.C.	86	65/215	-	-	116		Kinematically Stable	-
27		Kinematically Stable	-	57	42/305	W	S.C.	87	43/323	T	S.C.	117	44/265	W	S.C.
28	50/295	W	S.C.	58	35/317	T	S.C.	88	57/291	P	S.C.	118		Kinematically Stable	-
29	53/286	W	S.C.	59	39/291	W	S.C.	89	58/298	T	S.C.	119	60/266	W	S.C.
30	56/269	W	S.C.	60	46/297	T	S.C.	90	54/316	W	S.C.				

*: (-) Non-structurally controlled (highly weathered slope), T: Toppling, W: Wedge, P: Planar, S.C.: Structurally controlled

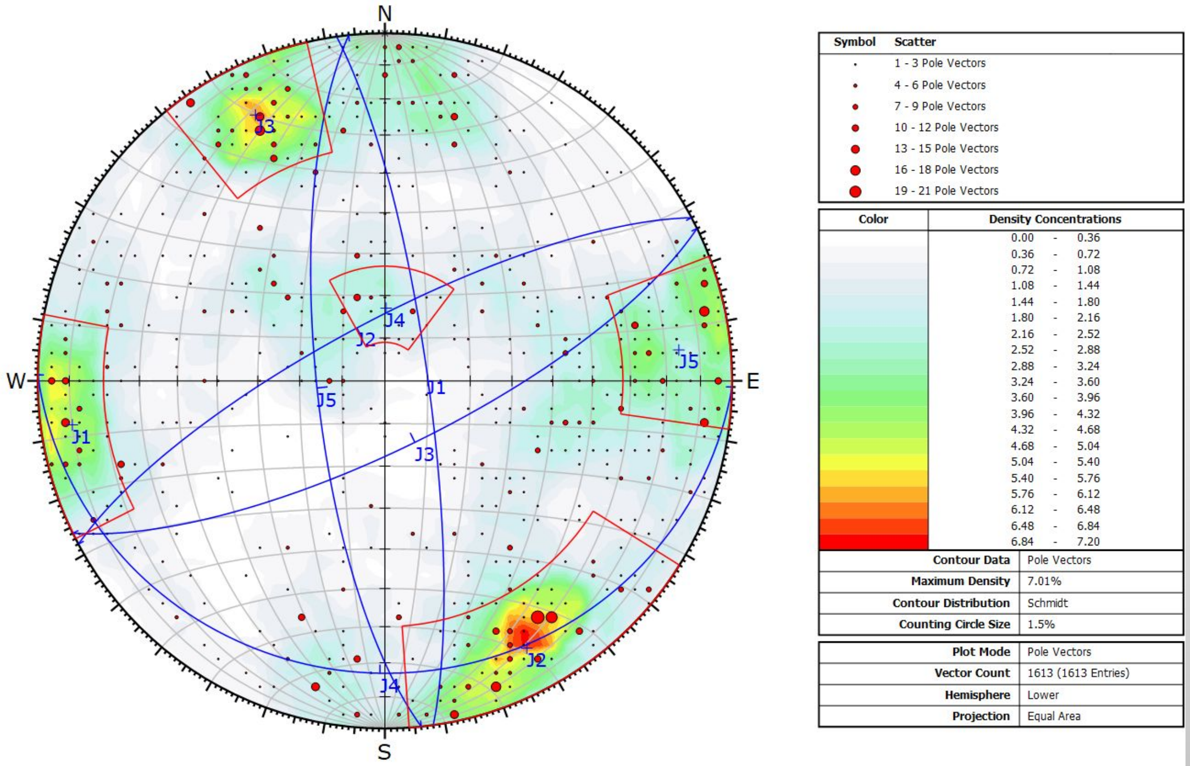

Figure 2—Contour diagram of discontinuity data recorded in the study area

Table II. Major discontinuity sets and their classification according to ISRM (2007)

Rock Mass Properties		Discontinuity Sets				
		J1	J2	J3	J4	J5
Orientation of discontinuity	Min-Max (D/DD)	72-88/072-097	60-82/320-341	59-84/146-164	10-22/153-208	81-89/251-261
	Mean	81/084	72 /329	71 /155	16/182	84 /255
	SD Dip	3.9	5.9	6.7	4	2.2
	SD Dip Direction	6.9	5.8	4.6	15.9	3
Spacing (m)	Minimum	0.1	0.1	0.05	0.1	0.1
	Maximum	1.5	1.2	2	1	1.8
	Mean	0.45	0.35	0.37	0.38	0.53
	SD	0.35	0.27	0.35	0.21	0.31
	Description	Moderate spacing	Moderate spacing	Moderate spacing	Moderate spacing	Moderate spacing
Persistence (m)	Range	2-8	2-3	1-1.5	5-10	6-12
	Description	Medium persistence	Low persistence	Low persistence	Medium persistence	High persistence
Roughness	Description	Discontinuity surfaces are generally rough undulating (IV. Class)				
Wall Strength	Highest-lowest Rebound (r)	10-56				
	Mean Rebound	26.45043				
	SD	8.872203				
	Grade	R2-R3				
	Description	Weak rock-Medium strong rock				
Aperture	Description	0.25-0.5 mm: Partly open/Closed Feature and/or 0.5-2.5 mm: Open/Gapped Feature				
Filling	Description:	Geometry: wall roughness. Filling type: weathering grade.				
Seepage	Seepage rating	III				
	Description: (Unfilled Discontinuities	The discontinuity is dry but shows evidence of water flow. i.e. rust strainin. etc.				

D/DD: Dip / Dip Direction. SD: Standard Deviation

- In addition, the Schmidt hammer test was conducted to measure the Uniaxial Compressive Strength (UCS) of discontinuity planes proposed by Barton and Choubey (1973). Experiments were carried out with L-type Schmidt hammer at a total of 119 different points.

As a result of the laboratory studies conducted by Kadakçı and Koca (2014) belonging to the same region, the unit weight values of orthogneisses were used (Table III). UCS values were calculated by using the following Equation [1] suggested by Barton and Choubey (1977). Orthogneiss rock slopes were determined to be "Moderately Strong" according to the Anon (1977) classification (Table IV).

Table III. Test results of orthogneiss mass (Kadakçı and Koca 2014)

Physico-Mechanical Parameters	n	Experiment results
γ (kN/m^3)	18	25.9±0.01
σ_{ci} (MPa)	12	27.34±5.30

n : Test number

$$LogJCS = 0.00088\gamma R + 1.01$$

In the above equation;
JCS: Strength of the discontinuity surface (MPa)
γ*:* Unit volume weight (kN/m^3)
R: Schmidt rebound value.

Table IV. Average UCS value obtained from Schmidt hammer test results of discontinuity planes at observation points

Number of Test	Highest-lowest Rebound	Mean Rebound	Standard Deviation	Mean log (JCS)	Mean UCS (MPa)	Grade	Description
119	10-56	26.45	8.87	1.49	32.9	R3	Medium Strong Rock

Slope Stability Assessments

1. Slope mass rating (SMR)

- SMR is a geotechnical classification system developed by Romana (1985) for rock slopes and obtained from basic RMR. It is calculated by adding a few adjustment factors to the basic RMR system. These adjustment factors are directly related to the relationship between the joints in the rock slope and the slope geometry. However, it also takes into account the excavation or blasting method. The SMR score calculated by subtracting from the RMR system is obtained with the given Equation [3].
- SMR=RMRbasic + (F1xF2xF3) +F4) [3]

- Where RMR is a system developed by Bieniawski (1973, 1989) to evaluate the quality of rock masses in engineering projects. The Rock Mass Rating (RMR) system is derived from the rock mass classification framework introduced by Bieniawski (1989), who formulated five principal parameters to systematically evaluate the discontinuity characteristics of rock masses. These parameters are UCS of intact rock, %RQD spacing between discontinuities, condition of discontinuities and groundwater, respectively. 4^{th} parameter of RMR was detailed by Bieniawski (1989) in order to define the discontinuity conditions of rock mass. The RMR system takes values ranging from 0 to 100 (Bieniawski, 1973).

- Other parameters given in the equation can be explained as follows. F1 is a parameter related to the dip direction of the discontinuity (or the plunge direction of the intersection line of two planes (ai)) and slope in the rock mass, αj and αs respectively (Anbalagan et al., 1992). F2 is explained as a parameter related to the dip of the discontinuity (βj) (or the angle of plunge of two discontinuities (βi) in the case of a wedge) that causes failure in the rock slope. This parameter is taken as 1.0 for toppling type failure (Romana, 1985). Both F1 and F2 can be calculated from the table as well as approximately calculated in Equation [4] and [5] developed by Romana (1993) as an alternatively.
- F1 = (1-sin │A│) 2 [4] , F2 = tan2 B [5]
- Another parameter, F3 is a parameter depend on the dips relationships between the joints and the slope surface, in fact, which the adjustment factor range between 0 and -60 developed by Bieniawski (Romana, 1993) (Table V). F4, which is the final correction factor, is an adjustment factor depending on the method of excavation or blasting in the rock slope (Romana, 1985) (Table VI). In addition to planar and toppling failure modes, wedge type failure was also described by Anbalagan et al., (1992) added and take into account for in the SMR system. In this article, 3 types of failure types namely planar, wedge and toppling were used as developed by Anbalagan et al., (1992).

Table V. Adjustment ratings for F1, F2, and F3 (Anbalagan et al., 1992)

Type of failure			Very favourable	Favourable	Normal	Unfavourable	Very unfavourable
P T W	A=	$\lvert\alpha_j-\alpha_s\rvert$ $\lvert\alpha_j-\alpha_s-180\rvert$ $\lvert\alpha_i-\alpha_s\rvert$	>30°	30-20°	20-10°	10-5°	<5°
P/T/W	F_1		0.15	0.40	0.70	0.85	1.00
P W	B=	β_j β_i	<20°	20-30°	30-35°	35-45°	>45°
P/W	F_2		0.15	0.40	0.70	0.85	1.00
T	F_2		1.00	1.00	1.00	1.00	1.00
P		$\beta_j-\beta_s$	>10°	10-0°	0°	0-(-10°)	≤(-10°)
W	C=	$\beta_i-\beta_s$	<110°	110-120°	>120°	-	-
T		$\beta_j+\beta_s$					
P/T/W	F_3		0	-6	-25	-50	-60

Failure: P planar; W wedge; T toppling. **Dip Direction**: αj discontinuity; αs slope. **Dip**: βj discontinuity; βs: slope

Table VI. Adjustment factor F4 for the method of excavation (Romana, 1985)

Excavation method (F4)			
Presplitting	+10	Blasting or mechanical	0
Smooth blasting	+8	Natural slope	+15
Natural slope	+15		

Table VII. Description of SMR classes (Romana, 1985)

Class	SMR	Description	Stability	Failures	Failure probability
I	81-100	Very good	Completely unstable	None	0
II	61-80	Good	Unstable	Some blocks	0.2
III	41-60	Normal	Partially stable	Some joints or many wedges	0.4
IV	21-40	Bad	Stable	Planar or big wedges	0.6
V	0-20	Very bad	Completely stable	Big planar or soil-like	0.9

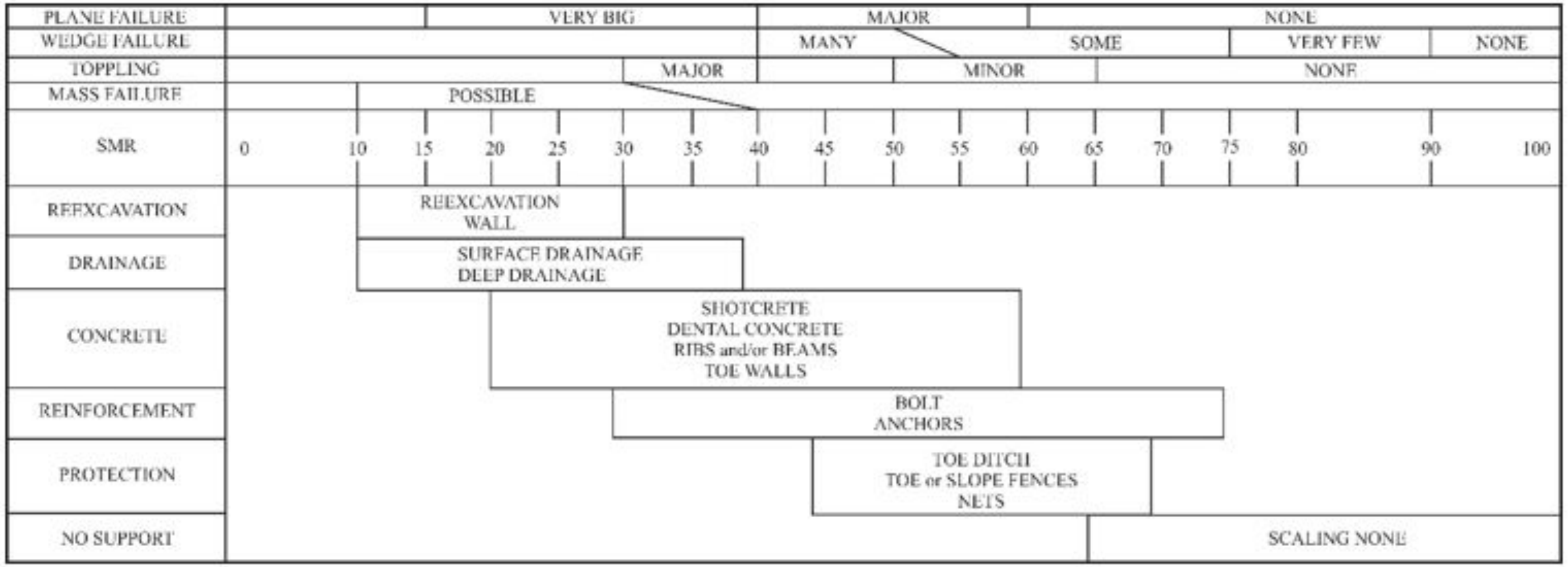

Figure 3—Suggested improvement methods for slopes (Romana et al., 2003)

2. QSlope

- Qslope is a geotechnical classification system developed by Barton and Bar (2015) for engineering studies such as slope and road cuts that use 6 different parameters, such as RQD, Jn, Jr, Ja, Jw and SRF, as in the Q-System. However, unlike the Q-system, several parameters have been updated and they proposed the following Equation [6] to estimate the Q-slope value (Barton and Bar, 2017).

- $Qslope = \frac{RQD}{J_n}\left(\frac{J_r}{J_a}\right)_0 \frac{J_{wice}}{SRF_{slope}}$ [6]

- The first 4 parameters in this equation are as in Qsystem (Barton et. al., 1974) and remained unchanged. Namely, rock quality definition, RQD (Deere, 1963) joint set number (Jn), joint roughness number (Jr), and joint alteration number (Ja) (Barton and Bar, 2017). RQD / Jn represents the block size. Jr / Ja is known as a friction resistance pair and can be applied to joints on either side of the wedge as needed (Barton, 2018). However, the adjustment factor for discontinuities in the rock slopes, that called the O-factor, has been developed by Barton and Bar (2015) and it is not available in the Qsystem. Another parameter is the environmental and geological condition number, which is used in this system as Jwice. This is different from

- Accordingly, slope stability is evaluated differently from the conventional Q-system, leading to the development of the Qslope classification with a revised structure (Barton and Bar, 2015). In case of slope reinforcement or drainage measures, adjustment factors are also included, and calculations of these adjustments are given also by Barton and Bar (2015). SRF slope is the stress reduction factor for the slope. SRFa has been developed to determine the physical conditions of the slope surface and can be scored from the suggested table by Barton (2015). SRFb is similarly used in the Q-index and is a parameter developed for the stress-strength on the slope. SRFb is a very considerable parameter for highly weathearing, weak and low strength materials in rock slope. However, it becomes more important as the slope and height of the slope increase (Barton and Bar, 2017). SRFc was developed for planes of weakness that adversely affect rock slopes in many aspect. SRFslope uses the maximum value between SRFa, SRFb and SRFc. The tables suggested by Barton and Bar (2015) enable the estimation of SRFa, SRFb, and SRFc values, respectively. In other words, Jwice / SRFslope is external factors and stress. The shear resistance, τ, can be approximated using Equation [7].

- $\tau = \sigma_n \tan^{-1}\left(\frac{J_r}{J_a}\right)$

- However, thanks to an equation developed by Barton and Bar (2015), the steepest slope angle that can remain stable without reinforcement or improvement can be readily calculated using Equation [8] and interpreted from Figure 4.

- $\beta = 20 log_{10} Q_{slope} + 65^o$ [8]

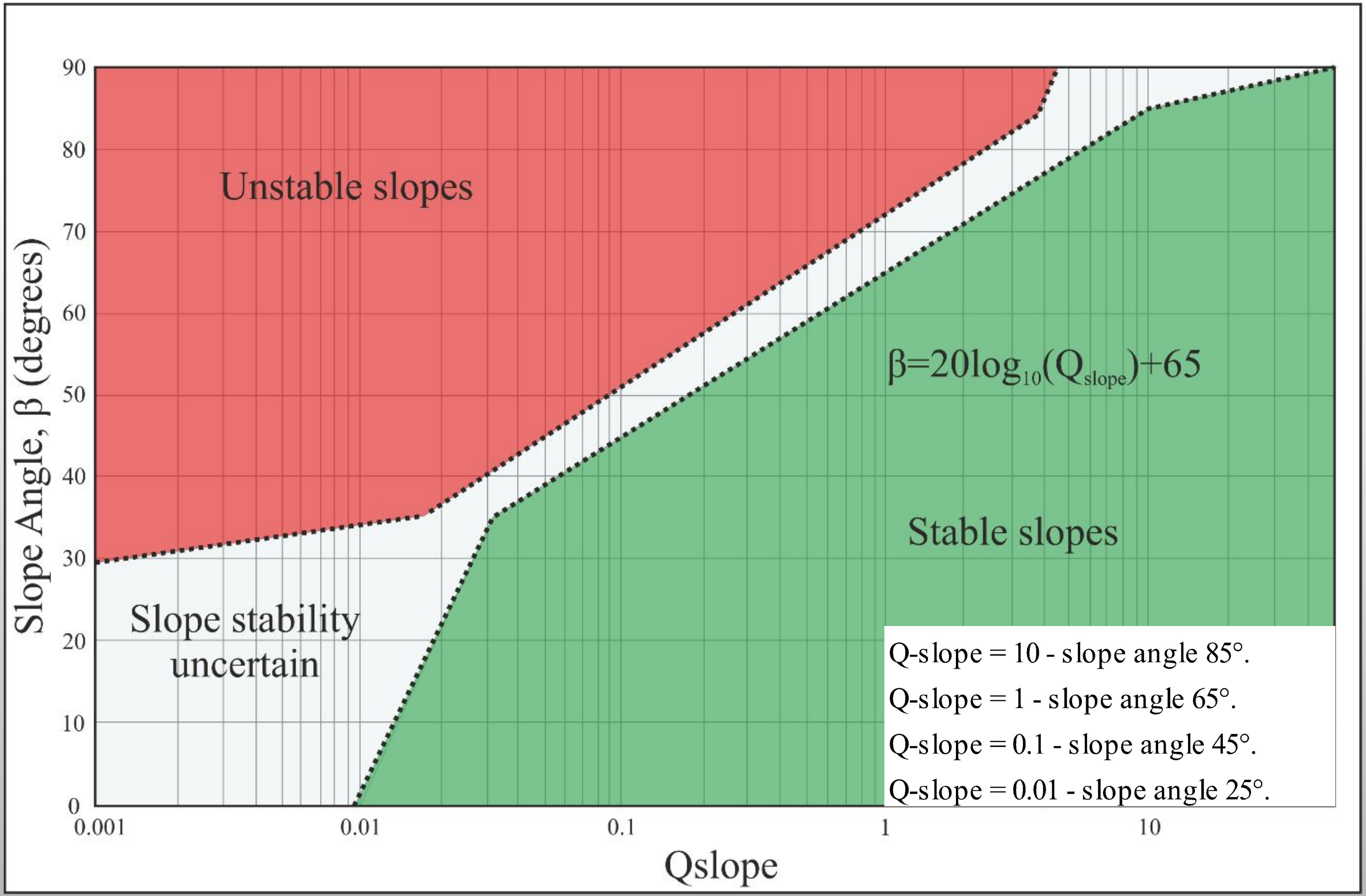

Figure 4—Q-slope stability chart (Barton and Bar, 2015)

Case Study

- In this study, an open pit mine opened in gneiss was chosen as study site. Albite production has been carried out in this open pit mine since 2004. It was determined by the total station measurements in the area where the eastern slopes move during heavy rainy periods in 2019. From the moment observed, production was completely stopped to prevent any loss of property or life. In addition to the use of SMR and Qslope systems to evaluate slope stability in this mine, the studies identified unstable slopes in the mine operation and recommended necessary improvement (such as re-excavation or surface drainage) and/or reinforcement works.

1. *Application of SMR*

- In order to use SMR classification, it is necessary to know the failure mechanism in the rock slope. The discontinuities taken from the 119 slopes in the eastern part of the open pit were transferred to the Dips V.7.016 (2019) software and the potential failure mechanism at each observation point was determined (Table I). Types of failures were detected in 76 of 119 rock slopes at the observation points. It was not included in the SMR system due to the loss of rock feature because of weathering in 43 observation points. After determining the failure mechanisms, RMR rock mass classification was conducted using all discontinuities data. The first 5 parameters used as input parameters in RMR classification were obtained from scanline measurements which is suggested by ISMR (2007).

- After the types of failures and RMR scores of 76 observation points were calculated. The input parameters required for SMR calculation were also collected from the field. In this process, joint and / or joint set and slope dip angle / dip direction measurements were obtained for each slope. In other words, each slope has been evaluated separately. SMR scoring, failure mechanisms and class of the mentioned slopes are presented in the Table IX .

Table IX. SMR scoring and adjustment factors for slopes

L	F.T	RMR	F1 value	F2 value	F3 value	F4 value	SMR score	Class	L	F.T	RMR	F1 value	F2 value	F3 value	F4 value	SMR score	Class
6	T	70	0.96	1	-25	8	54	III	63	W	63	0.19	0.70	-60	8	63	II
8	W	60	0.52	0.70	-60	8	46	III	68	W	73	0.85	0.85	-50	8	44	III
10	T	52	0.40	1	-25	8	50	III	70	W	50	0.23	0.40	-50	8	53	III
11	P	66	0.96	0.85	-50	8	33	IV	71	T	55	0.70	1	0	8	63	II
13	T	64	0.65	1	-25	8	55	III	73	W	55	0.15	0.40	-60	8	59	III
14	P	66	0.43	1.07	-50	8	51	III	74	W	59	0.83	0.70	-60	8	32	IV
18	W	61	0.13	0.21	-60	8	67	II	75	W	51	0.40	0.70	-60	8	42	III
20	W	66	0.77	0.39	-60	8	56	III	78	W	69	0.86	1	-50	8	34	IV
21	T	68	0.93	1	-6	8	70	II	79	W	60	0.80	0.40	-60	8	48	III
25	P	67	0.54	0.70	-60	8	52	III	80	T	63	0.85	1	-25	8	49	III
28	W	62	0.37	0.42	-60	8	60	III	81	W	57	0.70	0.85	-50	8	35	IV
29	W	62	0.85	0.61	-60	8	38	IV	82	W	59	0.85	0.85	-60	8	23	IV
30	W	60	0.77	0.25	-60	8	56	III	83	T	57	0.86	1	-25	8	43	III
31	W	58	0.16	0.23	-60	8	63	II	85	W	51	0.70	0.85	-50	8	29	IV
32	W	51	0.24	0.70	-60	8	49	III	87	T	57	0.93	1	-25	8	41	III
33	W	56	0.15	0.40	-60	8	60	III	88	P	64	0.93	1	-50	8	25	IV
34	P	42	0.28	1	-50	8	36	IV	89	T	52	0.28	1	-25	8	53	III
36	W	54	0.27	0.75	-60	8	50	III	90	W	50	0.72	0.45	-60	8	38	IV
37	W	60	0.70	0.40	-60	8	51	III	91	P	53	0.70	0.70	-50	8	36	IV
39	T	55	0.65	1	-6	8	59	III	92	W	62	0.68	0.45	-60	8	51	III
41	T	43	0.50	1	-25	8	38	IV	93	P	57	0.70	0.85	-60	8	29	IV
43	T	56	0.63	1	-25	8	48	III	94	W	51	0.70	0.85	-60	8	23	IV
44	W	62	0.10	1	-50	8	65	II	95	W	66	0.85	0.85	-50	8	37	IV
46	T	55	0.48	1	-25	8	51	III	96	T	48	0.70	1	-25	8	38	IV
48	W	56	0.11	0.39	-50	8	61	II	97	W	54	0.16	1	-60	8	52	III
49	P	56	0.19	0.85	-50	8	55	III	98	W	63	0.90	0.86	-60	8	24	IV
50	T	60	0.28	1	-6	8	66	II	99	T	63	1	1	-25	8	46	III
51	W	53	0.15	0.70	-60	8	54	III	103	W	52	0.47	0.56	-50	8	46	III
52	W	53	0.15	0.66	-60	8	55	III	105	W	49	0.23	0.85	-60	8	45	III
53	W	61	0.71	0.31	-60	8	55	III	107	T	48	0.43	1	-25	8	45	III
55	T	55	0.80	1	-25	8	43	III	108	P	58	0.70	1	-60	8	24	IV
56	W	65	0.74	0.20	-60	8	64	II	109	T	61	0.70	1	-25	8	51	III
57	W	61	0.13	0.20	-60	8	67	II	110	W	57	0.70	0.85	-60	8	29	IV
58	T	52	0.35	1	-6	8	57	III	112	W	50	0.10	0.40	-60	8	55	III
59	W	57	0.93	0.56	-50	8	39	IV	114	P	51	0.70	1	-50	8	24	IV
60	T	62	0.86	1	-25	8	48	III	115	W	54	0.16	1	-60	8	52	III
61	W	70	0.20	1	-50	8	68	II	117	W	51	0.85	0.85	-50	8	22	IV
62	T	70	0.40	1	-25	8	68	II	119	W	48	0.70	1	-60	8	14	V

L: Observation Point of Slopes, F.T. =Failure Type

- In the study area, 4 different SMR classes were identified, including 1 very bad, 22 bad, 41 normal and 12 good. The SMR value that falls within the very good range was not detected on any observation point. The very bad rock slope is the slope number 119 (Table IX). Although these studies were carried out in the summer, the algae and rust traces observed on the discontinuity planes at the 119th observation point is an indication that there has been observed water outflow on the slope during rainy periods. This caused the 119th Observation location to be classified as "very bad" due to the separating effect of water. However, the reason why none of the slopes are included in the “very good” class can be interpreted as the fact that the region is under tectonic regime and again, the groundwater in the region is at very high levels and the weathering effect is highly effective. Kinematically major type of failure mechanism in rock slopes are wedge type of failure with 58% (total number of 44 location) in previous sections. Based on Romana’s (1985) classification system, the third class comprises 54% of the slopes studied, representing a total of 41 locations. This ratio also belongs to the class most observed at observation points. In this classification system the possible failure modes specified in the Figure 5, namely "planar or big wedge" are kinematically compatible with the major failure mechanism in the open pit mine. This harmony can be easily observed on the slope number 32 (Figure 5). SMR class in the 32th slope is III and its kinematic failure mechanism is wedge. As seen in the Figure 5, the failure mechanism determined by Romana (1985) and the failure mechanism determined kinematically of a rock slope of SMR class III are similar. However, it can be observed in the stereographic projection that there may be a few planar failures at the same locations.

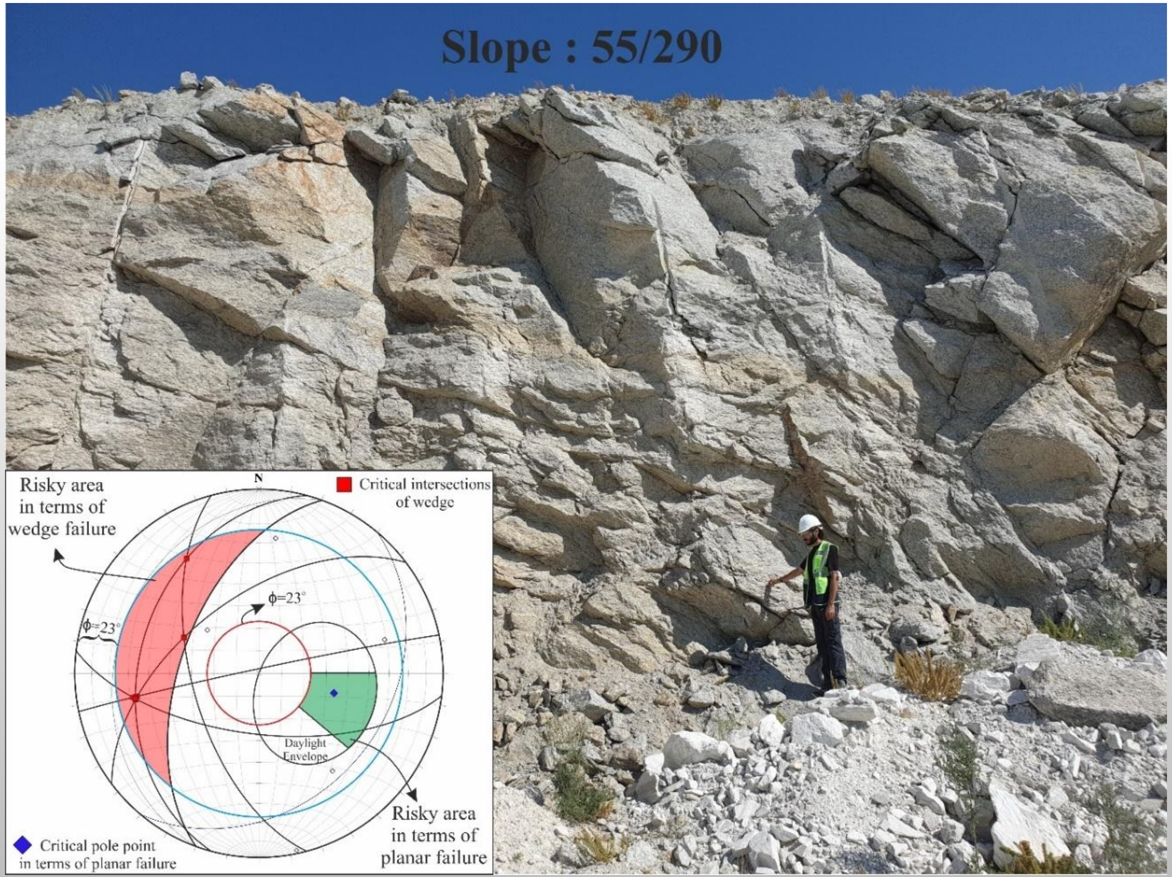

Figure 5—View of observation point 32 from the field and its kinematic analysis

- RMR scores in the rock slopes studied are between 42 and 73. SMR scores are between 14 and 70. In other words, it is seen that the SMR decreases the RMR score. As an exception, SMR score is higher than RMR score in 18 slopes (Figure 6).
- As can be seen from this graph the slopes numbered 18, 21, 31, 33, 39, 44, 48, 50, 51, 52, 57, 58, 63, 70, 71, 73, 89 and 112 are more than SMR points. This is because it can be said that the relationship between discontinuity and slope angles in the SMR system is more favorable than other rock slopes. This caused the SMR to be higher than RMR. In order to better interpret the SMR and RMR scoring made in the open pit and to evaluate the scores in the individual slope scale, the scoring has been depicted by using the IDW method via QGIS (3.30) software (Figure 7).

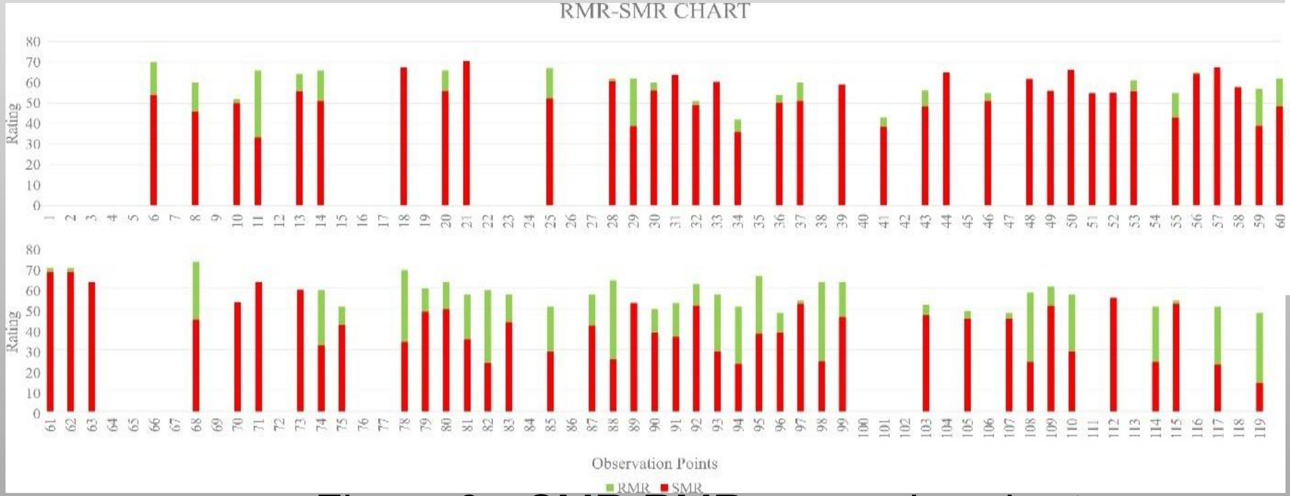

Figure 6—SMR-RMR comparing chart

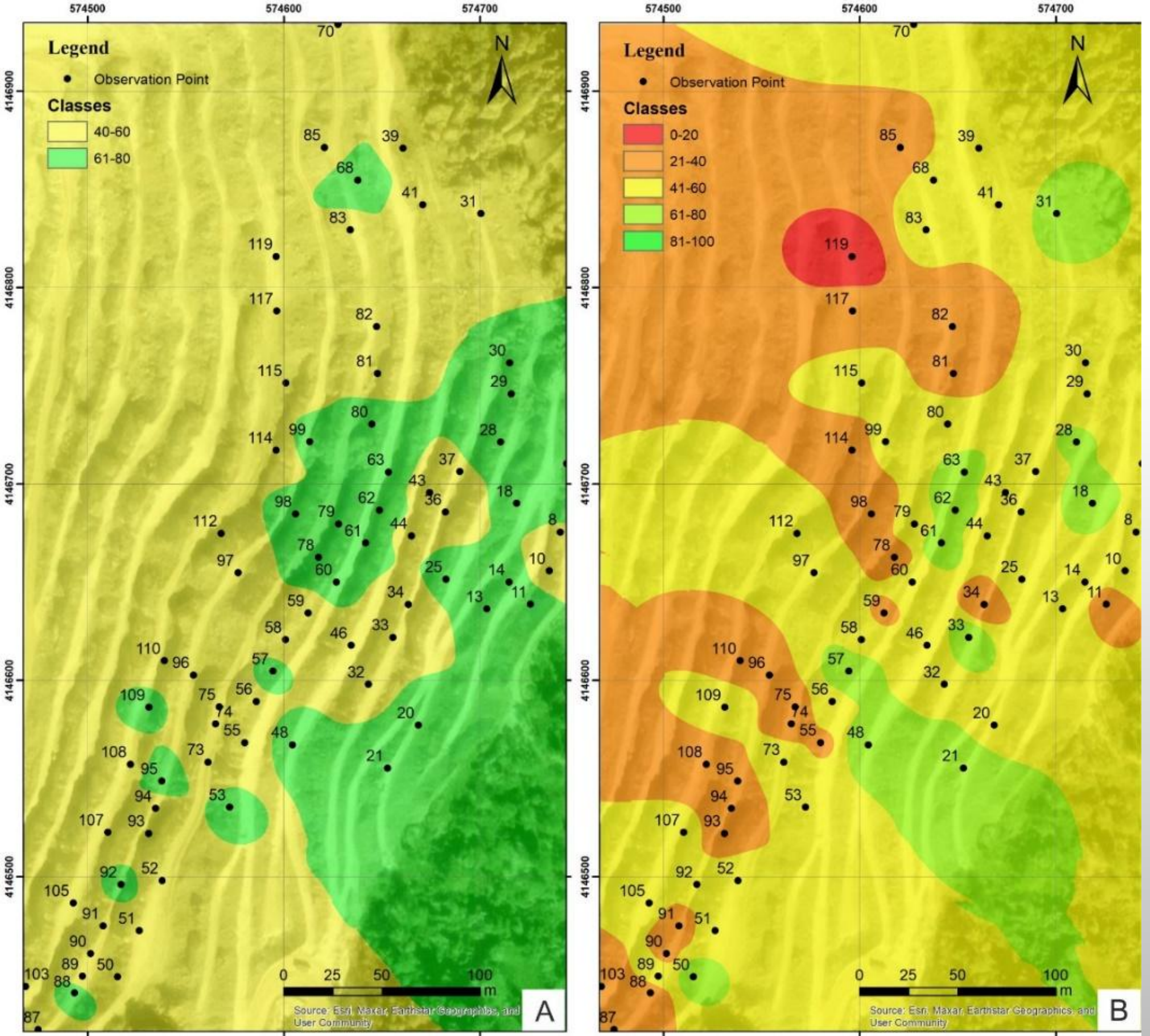

Figure 7—Thematic map of the scores in the study area created with the IDW method; (A) RMR map, (B) SMR map

- As can be seen in the figures, it is clearly observed that the adjustment factors in SMR scoring decrease the RMR score. According to the RMR scores given in the table, in any of the 76 rock slopes, it was not classified as "very bad rock" and "bad rock". In the classifications made on 76 rock slopes in SMR class, one of them was classified as very bad and 22 of them were bad. To be expressed as a percentage, the sum of slopes included in the very bad and bad rock class was determined as 30% in the SMR classification system, while this rate is 0% in the RMR system. Again, in the SMR system, the rock slope in the normal class (III) is 54%, while this rate is 64% in the RMR class. The most significant percentage difference belonging to the same rock slopes was determined in the rock class belonging to the "Good" class. While the rate of slopes in the "good rock (II)" class in the SMR system is 16%, this rate is calculated as more than twice in the RMR system, that is 36%.
- In addition to the SMR classification system, Romana (2003) has also proposed some improvement and support systems. Each of the 76 rock slopes studied on this figure developed by Romana (2003) is shown separately (Figure 8). As a result of the study on 76 slopes, different improvement and support methods were determined. There are no slopes belonging to the place shown with white background. In addition, details regarding the scores of the slopes are indicated in the legend. As can be seen from the Figure 8, in the improvement diagram made according to the SMR score, all slopes can suggest one or more improvement or strengthening. As previously stated, rock slopes classified as third class are densely distributed, as illustrated in (Figure 8).

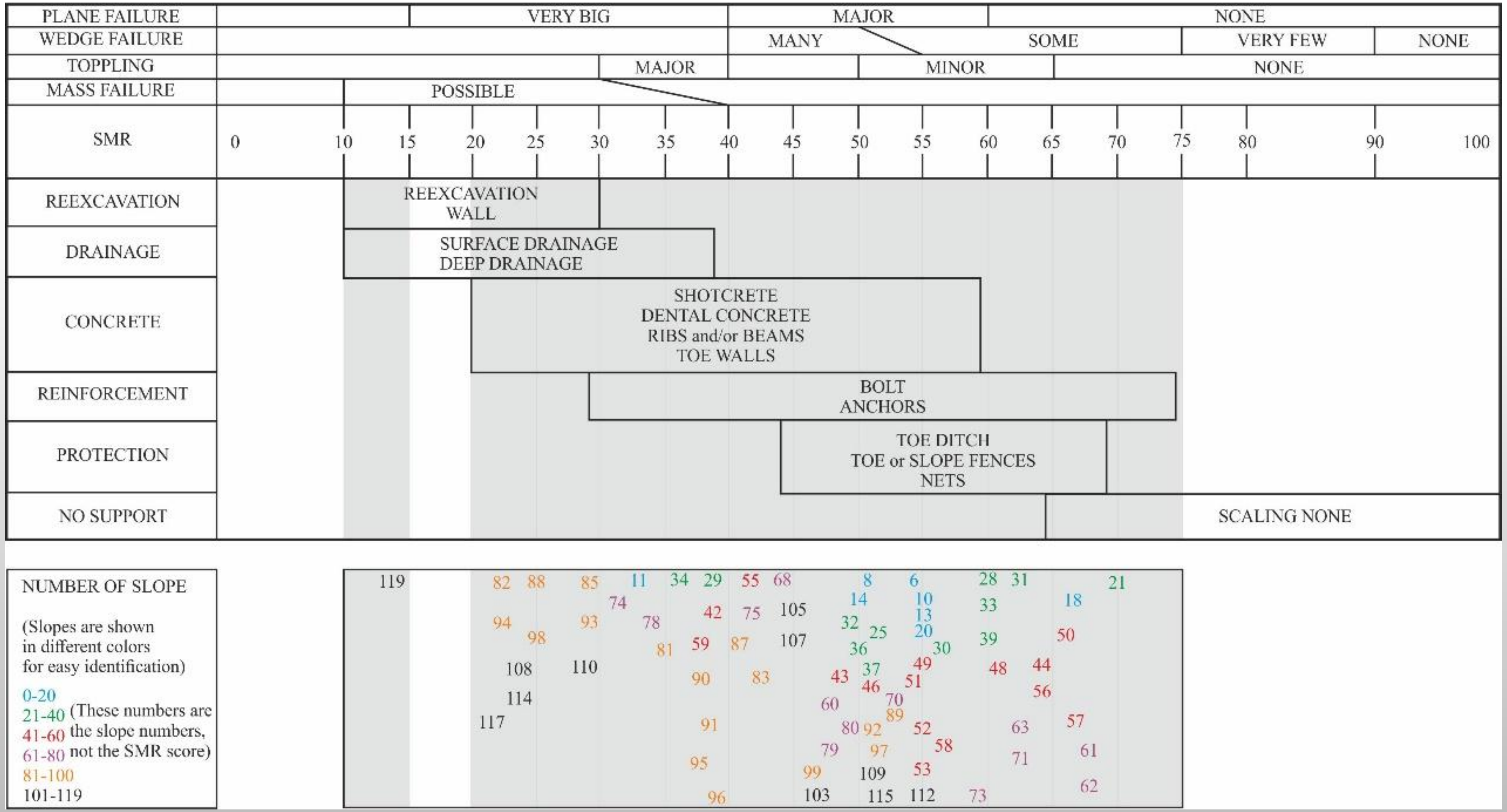

Figure 8—Showing the slopes in the study area in the support systems

- For example, slope number 46 has a score of 51.1. According to the improvements suggested by Romana (1985), many different improvements can be made on this slope such as shotcrete, bolt anchors and toe ditch. Another example can be given to slopes 119, 82, 98, 110. Improvement works for these slopes should be different than others. Improvement works such as re-excavation or surface drainage should be done on these slopes. The different comments that can be made for other slopes can be easily examined in the diagram developed by Romana (2003). It should not be forgotten that these reinforcement or support systems are only a guide. Different systems can be developed according to the production activity or the expenses of the contractor company.

2. Application of Q-Slope

- Qslope is another classification system used in this article to better examine and evaluate the slope stability. As mentioned in the slope stability assessment section, it is an empirical system developed by Barton and Bar (2015) in order to evaluate the rock slopes with different parameters and to determine the steepest slope angle that can remain stable without any reinforcement at the first stage of the project (Barton and Bar, 2017). Within the scope of this study, the slopes at 76 observation points in the open pit mine were scored based on the tables and equations suggested by Barton and Bar (2017). In the mining operation, all slopes were realized in orthogneiss mass, and all of the slopes have a height of less than 30 meters (average heights of the slopes of 10-12 meters). This example, inspired by Barton and Bar (2015), copies the existing information about this system. This illustrates the proper implementation of the technique at an albite mine located in Turkey. RQD value, which is one of the first 6 parameters of the formula developed specifically for this system, is a parameter used in the RMR system, which is necessary for calculating SMR, the values were utilized based on the calculations performed using the RMR system outlined in the preceding section. Another parameter of the formula, Jn (number of discontinuous sets) was determined as a result of scanline measurements. It should be noted here that the measurements taken for each slope are unique and have been considered independently of other slopes. Jr/Ja is evaluated differently for each slope outcrop. Here, it was scored for the most unfavorable joint set as suggested for the O-factor developed by Barton and Bar (2015). In wedge-type failures, the secondary joint set that causes failure was given appropriate scores, also developed by Barton and Bar (2015). In order to calculate Jwice, which is another parameter developed differently from the Q system, the amount of precipitation and temperature that the region falls according to months by using the local meteorological resources of the country.

- Based on these data, the 'Wet Environment' class was selected as one of the categories recommended by Barton and Bar (2015). The reason for this is that as can be seen from the data, the region receives heavy rainfall, especially in winter, and the average temperature is low during these rainy periods. During the investigations carried out in the summer periods, it was determined that the slope steps were stable (production stopped), but because of the characteristics of the discontinuity of planes on the slopes (orientation, roughness, spacing, etc.) it was found to be "incompetent" rock. In other words, for this study, the Jwice value of each slope was determined as 0.6. In addition, when there was no drainage and / or reinforcement system in the proposed graph in any bench of the pit slopes, it was not multiplied by any coefficient. Observation points for the SRFa parameter were evaluated separately. As a result of these observations, it was thought that there were large block falls on the slopes due to blasting and there was a rock slope sensitive to weathering. Considering these situations, the B Description class suggested in the scoring system for the rock slope is given, namely “Loose blocks, signs of tension cracks and joint shearing, susceptibility to weathering, severe disturbance from blasting”. One of the parameters required to define the SRFb parameter is UCS, and this parameter was determined empirically by using L- Type Schmidt hammer in the field. The second parameter is the maximum principal stress. This parameter is calculated by RocLab V.0.1 software by following Generalized Hoek and Brown failure criterion (Hoek and Brown, 1997) for jointed rock mass (RocScience, 2007). As a result of these operations, $\sigma c / \sigma 1$ value was calculated and SRFb score was found. The SRFc value, which is the last denominator of the system, was again realized by defining the main discontinuity sets from the observation points. A different SRFc score was found for each slope. According to Barton and Bar (2015), the highest value of SRFa, b, c, values were included in the calculation. At the end of all these processes, after the necessary calculations were made at 76 observation points, the Qslope score of each slope was revealed (Table X).

Table X. Q slope values of slopes at observation locations

Location	RQD/Jn	(Jr/Ja)*(O-fac)	(Jr/Ja)*(O-fac)	Jwice/SRF(a,b,c)	Q Slope VALUE	Location	RQD/Jn	(Jr/Ja)*(O-fac)	(Jr/Ja)*(O-fac)	Jwice/SRF(a,b,c)	Q Slope VALUE
6	15.500	1.125	1	0.12	2.093	63	5.667	2.250	2.7	0.12	4.131
8	7.083	1.125	1.35	0.12	1.291	68	6.917	0.375	0.45	0.12	0.140
10	12.167	1.125	1	0.12	1.643	70	4.867	0.250	0.4	0.12	0.058
11	30.000	1.000	1	0.12	3.600	71	3.920	0.563	0.675	0.12	0.179
13	6.000	0.375	1	0.12	0.270	73	5.067	0.563	0.675	0.12	0.231
14	15.000	1.500	1	0.12	2.700	74	5.667	0.281	0.338	0.12	0.065
18	5.333	0.750	1.2	0.12	0.576	75	3.333	0.563	0.675	0.12	0.152
20	14.167	0.750	1.2	0.06	0.765	78	5.267	0.563	0.675	0.12	0.240
21	10.333	0.188	0.8	0.12	0.186	79	5.400	1.125	0.675	0.12	0.492
25	7.083	1.500	0.8	0.12	1.020	80	3.867	0.375	1	0.12	0.174
28	5.667	0.375	0.6	0.12	0.153	81	4.867	0.188	0.3	0.12	0.033
29	5.533	0.375	0.6	0.12	0.149	82	5.128	0.281	0.338	0.12	0.058
30	4.600	0.750	1.2	0.12	0.497	83	4.905	0.375	1	0.12	0.221
31	6.333	0.563	1.35	0.12	0.577	85	5.791	0.094	0.338	0.12	0.022
32	5.267	0.563	0.675	0.12	0.240	87	5.595	0.188	1	0.12	0.126
33	5.400	0.375	0.6	0.12	0.146	88	15.347	0.188	1	0.075	0.216
34	5.333	0.188	1	0.12	0.120	89	4.298	0.563	1	0.12	0.290
36	4.267	0.563	0.675	0.12	0.194	90	4.905	0.375	0.6	0.12	0.132
37	6.583	0.375	0.6	0.12	0.178	91	5.128	0.125	1	0.12	0.077
39	4.267	0.375	0.8	0.12	0.154	92	5.704	1.125	1.35	0.12	1.040
41	2.667	0.375	0.8	0.12	0.096	93	4.953	0.563	1	0.12	0.334
43	6.333	0.375	1	0.12	0.285	94	3.472	0.375	0.75	0.12	0.117
44	7.083	1.125	1.35	0.12	1.291	95	5.880	0.188	0.6	0.12	0.079
46	5.400	0.375	1	0.12	0.243	96	2.707	0.375	1	0.12	0.122
48	6.083	0.375	0.6	0.12	0.164	97	5.791	0.563	0.675	0.12	0.264
49	10.667	0.125	1	0.12	0.160	98	6.067	0.375	0.6	0.12	0.164
50	6.583	0.563	1	0.12	0.444	99	6.000	0.750	1	0.12	0.540
51	4.167	0.563	0.675	0.12	0.190	103	4.267	0.188	1	0.12	0.096
52	4.600	1.125	0.75	0.12	0.466	105	2.667	0.750	1.2	0.12	0.288
53	7.083	0.375	0.6	0.12	0.191	107	4.000	0.375	1	0.12	0.180
55	4.867	0.188	1	0.12	0.110	108	5.133	0.375	1	0.12	0.231
56	6.133	0.750	1.2	0.12	0.662	109	5.400	0.375	1	0.12	0.243
57	7.333	1.125	1.35	0.12	1.337	110	5.267	0.375	0.6	0.12	0.142
58	8.778	0.563	1	0.12	0.593	112	5.667	0.375	0.6	0.12	0.153
59	7.083	0.563	0.675	0.12	0.323	114	6.667	0.375	1	0.12	0.300
60	6.000	0.750	1	0.12	0.540	115	4.663	0.375	0.6	0.12	0.126
61	6.000	2.250	2.7	0.12	4.374	117	3.114	0.188	0.3	0.12	0.021
62	6.133	1.125	1	0.12	0.828	119	2.667	0.375	0.6	0.12	0.072

- After the Qslope scores were calculated, they were placed in the semi-logarithmic table proposed by Barton and Bar (2015) (Figure 9). All rock slopes are indicated by black points. According to this classification system, 31 stable, 27 unstable and 18 uncertain classes were determined as a result of the analyzes performed on a total of 76 slopes. The proportional values of these classes were determined as 41%, 35% and 24%, respectively.

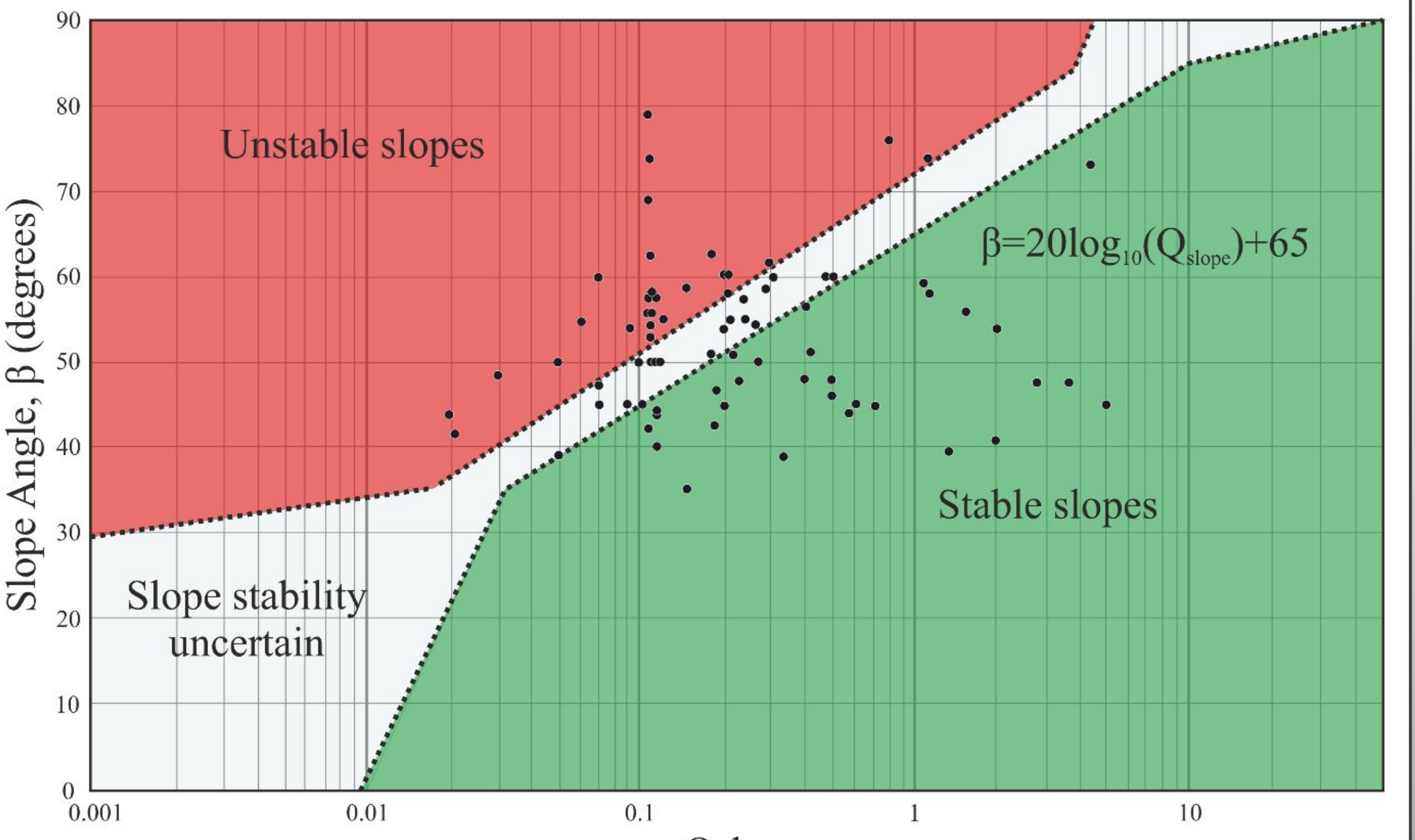

Figure 9—Classification of slopes in Qslope

Table XI. Classification of the steepest slopes compared to existing slopes according to the proposed Equation [9].

- $\beta = 20 \log_{10} Q_{slope} + 65^o$ [9]

- It is possible to classify the rock slope by comparing the current slope angles of the aforementioned slopes and the steepest slope angles produced by the formula developed by Barton and Bar (2015). In the analysis made within the scope of this study, the steepest slope angle was determined by both methods (Table XI).

Location	Current slope angle	Steepest slope angle	Qslope Class	Location	Current slope angle	Steepest slope angle	Qslope Class	Location	Current slope angle	Steepest slope angle	Qslope Class	Location	Current slope angle	Steepest slope angle	Qslope Class	Location	Current slope angle	Steepest slope angle	Qslope Class
6	41	71.4	S	39	74	48.7	UnS	**63**	45	77.3	S	92	54	65.3	S
8	58	67.2	S	41	54	44.6	UnS	**68**	44	47.9	S	93	60	55.5	UnC
10	56	69.3	S	43	54	54.1	UnC	**70**	39	40.3	UnC	94	50	46.4	UnC
11	48	76.1	S	44	73	67.2	UnS	**71**	79	50.0	UnS	95	45	43.0	UnC
13	50	53.6	S	46	47	52.7	S	**73**	51	52.3	S	96	56	46.7	UnS
14	48	73.6	S	48	40	49.3	S	**74**	55	41.2	UnS	97	55	53.4	UnC
18	48	60.2	S	49	44	49.1	S	**75**	63	48.6	UnS	98	55	49.3	UnS
20	45	62.7	S	50	47	58.0	S	**78**	57	52.6	UnC	99	60	59.6	UnC
21	47	50.4	S	51	51	50.6	UnC	**79**	60	58.8	UnC	103	45	44.6	UnC
25	59	65.2	S	52	53	58.4	S	**80**	50	49.8	UnC	105	54	54.2	UnC
28	50	48.7	UnC	53	43	50.6	S	**81**	48	35.3	UnS	107	63	50.1	UnS
29	53	48.5	UnS	55	45	45.8	S	**82**	50	40.3	UnS	108	60	52.3	UnS
30	56	58.9	S	56	41	61.4	S	**83**	45	51.9	S	109	60	52.7	UnS
31	44	60.2	S	57	39	67.5	S	**85**	42	31.8	UnS	110	56	48.1	UnS
32	55	52.6	UnC	58	35	60.5	S	**87**	43	47.0	S	112	58	48.7	UnS
33	50	48.3	UnC	59	39	55.2	S	**88**	57	51.7	UnS	114	62	54.5	UnS
34	57	46.6	UnS	60	46	59.6	S	**89**	58	54.3	UnC	115	68	47.0	UnS
36	57	50.8	UnS	61	73	77.8	S	**90**	54	47.4	UnS	117	44	31.5	UnS
37	58	50.0	UnS	62	76	63.4	UnS	**91**	47	42.7	UnC	119	60	42.1	UnS

Stable: S, UnCertain: UnC, Unstable:UnS

- According to the results of Qslope on 76 slopes, 18 uncertain classes were determined. These slopes can become stable in the classification system empirically made even by only reducing the slope angles by a few degrees. To give an example, the slope number 51 is included in the stable class only by reducing the angle with a difference of 0.43 degrees. In other words, the slope can become stable in relation to the material properties with the necessary slope angle reduction process that can be made on slopes. However, the openings of several slopes that appear to be "stable" in the table were reduced more than necessary. This increases the cost of excavation and causes loss of time. Some of the mentioned slopes can be given as 18, 31, 48, 56, 57 and 63. Classes were depicted by IDW method using QGIS program to show the spread of Qslope classification in the field and slope scale. During this mapping process, the classification developed by Barton and Bar (2015) was used. Since the program uses the IDW method only as a numerical value, stable slopes are given 1, uncertain slopes 0, and unstable slopes -1 values. Following the coding process, its spatial distribution was illustrated on the mining area located on a slope of 76°, using the IDW interpolation method (Figure 10).

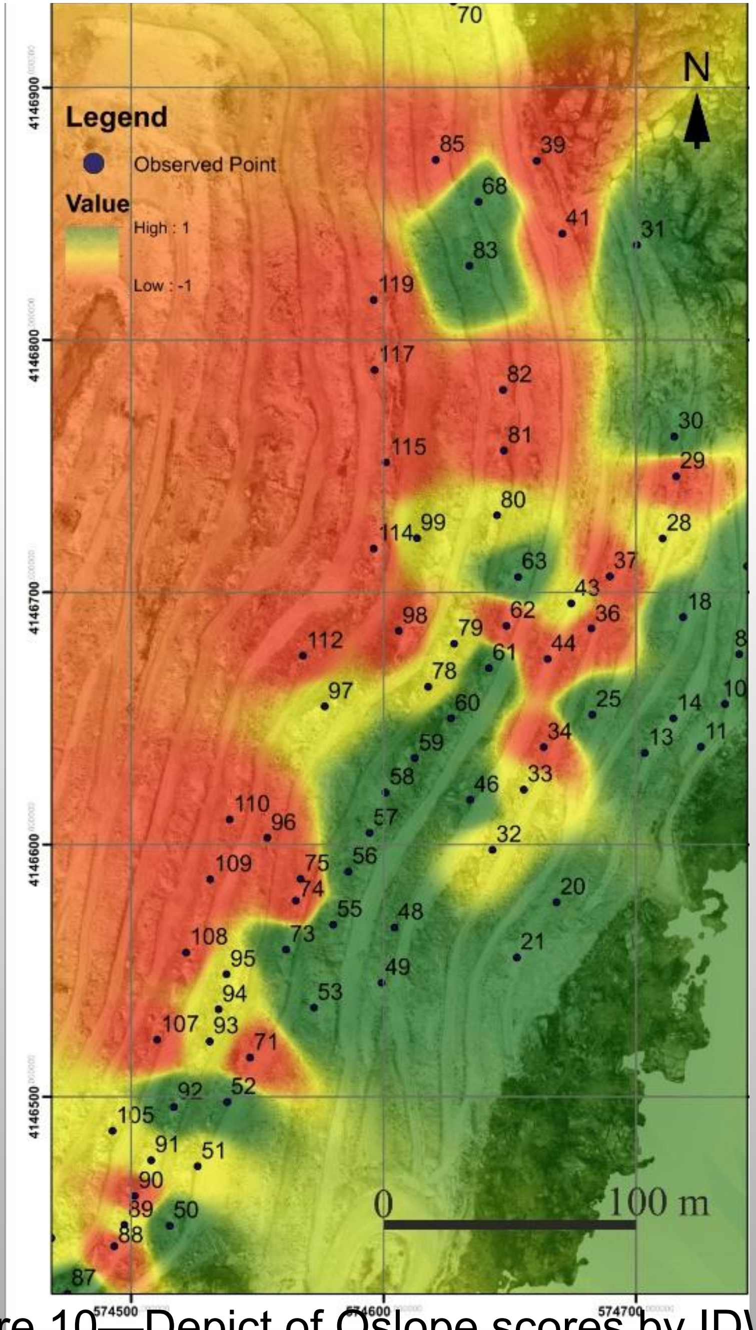

Figure 10—Depict of Qslope scores by IDW method

Results

- The research area is located within the Menderes Massif, an important tectonic zone of the Anatolides prominent in Western Anatolia (Graciansky, 1965). This study used the scan-line technique advocated by ISRM (2007) and covered 119 observation points in the eastern part of the albite open-pit mine that opened in geneiss (Figure 1). A total of 1613 discontinuity measurements were carried out at these points and the data, including discontinuity orientation, spacing, persistence and roughness, were evaluated according to ISRM (2007) guidelines. As a result, the dominant failure type detected was wedge (58%).

- In light of the kinematic failure potential observed in this mining region, two rock mass classification systems have been used: SMR and Qslope. For SMR classification, kinematic failure type have to be evident. Four SMR classes were identified in the study area: 1 very poor, 22 poor, 41 fair, and 12 good. No slopes fell into the "very good" range due to the tectonic activity of the region and high groundwater levels tend to exacerbate the effects of weathering. The majority of the observed failures (58%) were wedge failures.

- In the 76 slopes examined, various improvement and support methods were suggested according to Romana (1985). These methods range from shotcrete and bolt anchors to re-excavation and surface drainage, depending on slope characteristics. Additionally, slopes at 76 observation points were scored using Barton and Bar (2017) tables and equations and the relevant Qslope scores were revealed (Table X). According to this classification system, 31 slopes were evaluated as stable, 27 slopes as unstable and 18 slopes as uncertain. The rates of these classes are 41%, 35% and 24% respectively. In particular, slopes 18, which were initially classified as uncertain, were able to achieve stability with slight angle adjustments, as was the case of slope 51, which was classified as stable with an angle reduction of only 0.43 degrees.
- According to field observations and classification systems, many slopes in both systems can be defined as “Unstable”. Examples of this are presented in Table XII. As a result of the analysis, it is clearly observed that the slopes numbered 29, 34, 41, 74, 81, 82, 82, 85, 88, 90, 96, 98, 98, 108, 110, 114, 117, 119 are observed as “Unstable” in both classification systems. The reason for this is that these slopes are extremely altered (HW) and the fracture-cracks are extremely intense. It was observed that UCS and %RQD values were low on the slope surfaces and therefore the slopes were extremely unstable in both classification systems. On the other hand, some slopes were classified as "Stable" in the Qslope System, while some slopes were classified as "Unstable" in the SMR. These slopes are observation points 11 and 59. The reason for this is that the "Current Slope Angle" value in the Qslope classification system is considerably smaller than the "Maximum Slope Angle" value. Since this value is not observed in the SMR system, differences are observed in both classification systems. Besides, the opposite situation was also observed. In other words, some slopes classified as "Unstable" in the Qslope were classified as "Stable" in the SMR. The slopes in question are slopes 44, 62 and 71. The reason for this is that the UCS and %RQD values are very high. Therefore, RMR and consequently SMR values are high. However, since the slope angle is extremely steep, the class of the slopes is considered to be "Unstable" in the Qslope (Table

- As a result of this study on gneiss rock slope, it is thought that the use of both classification systems in terms of providing very practical and fast information in pre-stabilization studies will guide future studies. It is expected to give more accurate results qualitatively due to the kinematic analysis for the use of the SMR system, followed by the use of the RMR classification system. In the next stage of the study, the "slopes with sliding potential" observed in the region can be studied in more detail and the "Factor of Safety (FS)" can be calculated on these slopes by numerical analysis method, and by comparing the values calculated both numerically and kinematically, the studies can be continued with the safest and maximum efficiency.

Table XII. Comparison of Qslope and SMR classification system

Location	Qslope Class	SMR Class	Location	Qslope Class	SMR Class	Location	Qslope Class	SMR Class	Location	Qslope Class	SMR Class
6	S	III	39	UnS	III	63	S	II	92	S	III
8	S	III	41	UnS	IV	68	S	III	93	UnC	IV
10	S	III	43	UnC	III	70	UnC	III	94	UnC	IV
11	S	IV	44	UnS	II	71	UnS	II	95	UnC	IV
13	S	III	46	S	III	73	S	III	96	UnS	IV
14	S	III	48	S	II	74	UnS	IV	97	UnC	III
18	S	II	49	S	III	75	UnS	III	98	UnS	IV
20	S	III	50	S	II	78	UnC	IV	99	UnC	III
21	S	II	51	UnC	III	79	UnC	III	103	UnC	III
25	S	III	52	S	III	80	UnC	III	105	UnC	III
28	UnC	III	53	S	III	81	UnS	IV	107	UnS	III
29	UnS	IV	55	S	III	82	UnS	IV	108	UnS	IV
30	S	III	56	S	II	83	S	III	109	UnS	III
31	S	II	57	S	II	85	UnS	IV	110	UnS	IV
32	UnC	III	58	S	III	87	S	III	112	UnS	III
33	UnC	III	59	S	IV	88	UnS	IV	114	UnS	IV
34	UnS	IV	60	S	III	89	UnC	III	115	UnS	III
36	UnS	III	61	S	II	90	UnS	IV	117	UnS	IV
37	UnS	III	62	UnS	II	91	UnC	IV	119	UnS	V

Stable: S, UnCertain: UnC, Unstable: UnS

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Slope Stability Evaluation of Gneiss Rock Slopes Using SMR and QSlope

Presenter: Ph.D. (c) Geo. Eng. (M.Sc.) **Enes KALHAN**[1]

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