Assessment of Slope Stability of Various Cut Slopes with Effects of Weathering by Using Slope Stability Probability Classification (SSPC)

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1. INTRODUCTION

Road cuts created next to highways pose a problem for human life. Disturbances on road cuts such as changing the geometry, widening the apertures of discontinuities with excavation and stress relief eventually increase the weathering on the slope facet can affect the stability. The change on stability combining with a wrong design on a cut slope can come up with a critical incident. The purpose of this study is assessing stabilities of different kind of road cuts by using SSPC system.

DETERMINISTIC

- Limit Equilibrium Method (LEM)
- Finite Element Method (FEM)
- Strength Reduction Method (SRM) etc.

PROBABILISTIC

- Regression analysis
- Variance propagation
- Monte Carlo sampling etc.

SSPC

Due to the importance of the uncertainties such as strength, rock quality designation and discontinuities in geotechnical designs, it is important to consider probabilistic approaches. In order to overcome these uncertainties because of these inputs, Hack (1998) developed Slope Stability Probability Classification (SSPC) by placing less influence on strength than other mass rating systems (Lindsay et al., 2001) and focusing on discontinuity parameters (Canal & Akın, 2016).

SSPC SYSTEM

SSPC is a probabilistic classification system considering weathering degree and excavation type, and having Exposed Rock Mass (ERM) Number 2 (Figure 1), Reference Rock Mass (RRM) (Figure 1) and Slope Rock Mass (SRM) Number 3 (Figure 1).

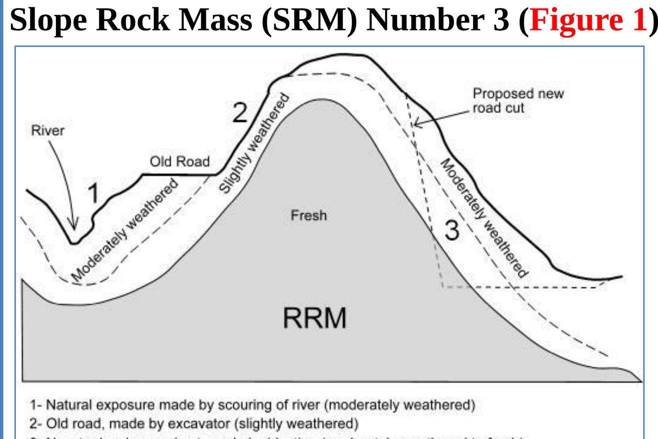
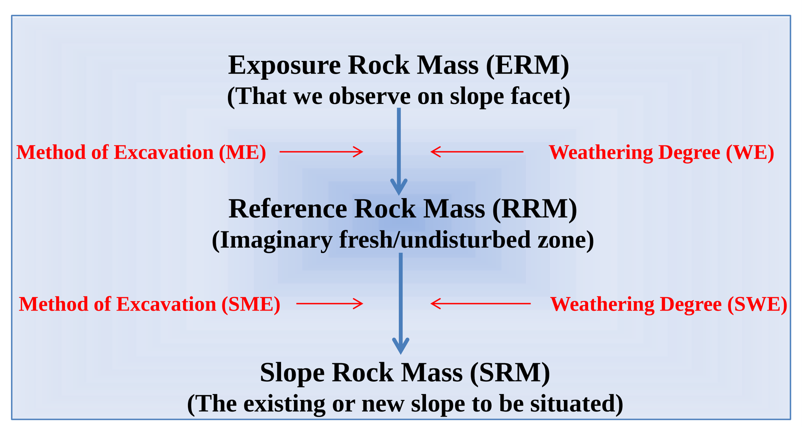


Figure 1. Sketch of view rock masses with various degrees of weathering (Modified from Hack et al. (2002)).



STUDY AREA

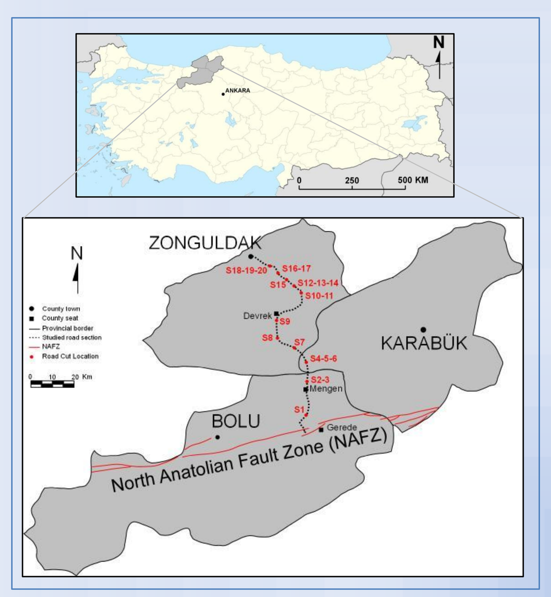


Figure 2. Location map of the study area.

The study area is located at North West Black Sea region in Turkey (Figure 2). 20 road cuts (Figure 3) which are located in North West Black Sea region of Turkey were evaluated by SSPC. Six different rock types - mudstone, sandstone, limestone, granite, basalt and granodiorite - are encountered at these road cuts. The North Anatolian Fault Zone (NAFZ) is located southern part of the study area (Figure 2). The road cuts from 1 to 9 and 10 to 20 are located in the 1st and 2nd degree earthquake zones, respectively (GDDA, 1996). Throughout the study area, road cuts are determined to be mostly highly jointed on the slope facets. Considering these preliminary information, these road cuts are prone to fail with different mechanisms.

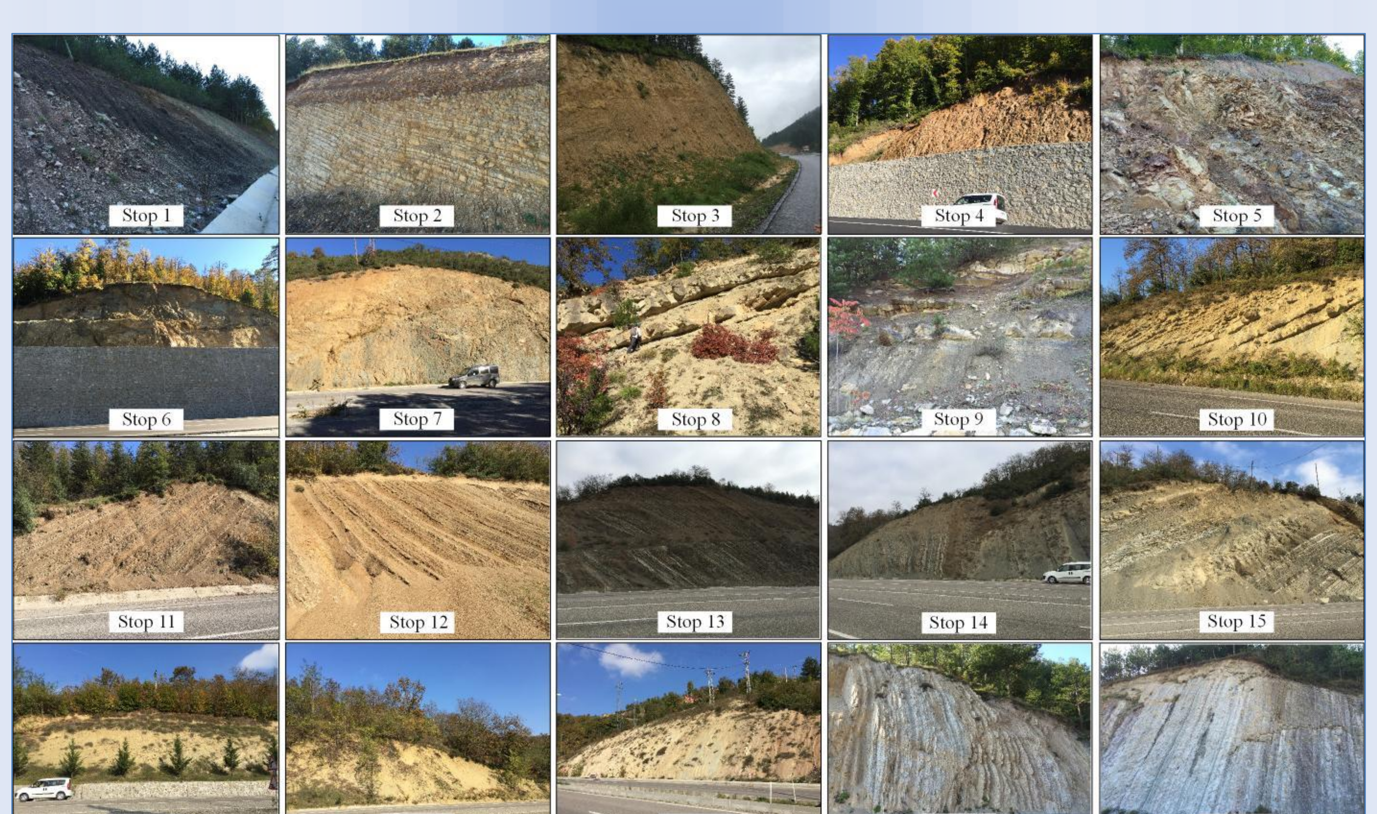


Figure 3. General views of studied road cuts.

2. SLOPE STABILITY PROBABILITY CLASSIFICATION (SSPC)

SSPC introduces a very easy data collection, therefore all the data were gathered according to this system in the field. Parameters needed for the Exposure Rock Mass (ERM) which are UCS, Excavation type, Weathering degree, Slope height and orientation, and stability condition are given in Table 1 and Discontinuity properties in Table 2. Data collection, reference rock mass (RRM) and slope rock mass (SRM) properties, and stable probabilities against orientation dependent/independent are given in Table 3 as a sample for Stop 8.

Table 1. Exposure rock properties at each road cut

Road Cut	UCS (MPa) Fresh Dry	Fresh Sat.	Weathered Dry	Weathered Sat.	Excavation Type	Weathering Degree	Slope Height (m)	Slope Dip°/Dip Direction°	Slope Stability
1	29,79	11,92	27,03	7,63	Mechanical	Moderately	8	40/310	Small Problems
1-F	26,30	4,20	22,80	1,50	Mechanical	Highly	8	40/310	Large Problems
2	39,82	38,21	28,48	15,98	Mechanical	Moderately	10	60/245	Small Problems
2-F	16,20	8,00	13,42	7,21	Mechanical	Moderately	10	60/245	Large Problems
3	39,82	38,21	9,78	8,25	Mechanical	Moderately	15	70/045	Small Problems
4	21,31	18,25	7,74	5,66	Mechanical	Moderately	12	50/215	Small Problems
5	52,66	38,85	22,24	3,42	Mechanical	Moderately	20	50/200	Small Problems
6	21,31	18,25	8,60	5,10	Mechanical	Moderately	10	75/290	Small Problems
7	114,94	88,03	23,67	12,48	Mechanical	Moderately	15	75/295	Small Problems
8	33,60	23,29	23,17	13,09	Mechanical	Highly	15	65/245	Small Problems
9	73,95	55,95	46,80	24,40	Mechanical	Slightly	8	75/180	Small Problems
10	36,92	17,55	14,54	7,38	Mechanical	Moderately	8	45/310	Small Problems
11	25,94	21,20	14,22	6,23	Mechanical	Moderately	6	60/260	Small Problems
12	18,24	10,17	17,18	5,75	Mechanical	Highly	6	50/240	Small Problems
13	22,03	10,74	15,18	6,34	Mechanical	Moderately	20	70/225	Small Problems
14	22,92	14,36	21,05	11,91	Mechanical	Moderately	15	50/215	Small Problems
15	37,96	27,48	34,30	21,28	Mechanical	Moderately	15	50/195	Small Problems
16	26,93	12,95	21,62	12,65	Mechanical	Moderately	6	55/200	Small Problems
17	17,75	11,38	11,62	7,58	Mechanical	Moderately	6	45/185	Small Problems
18	34,93	17,69	28,83	14,54	Mechanical	Moderately	10	45/240	Small Problems
19	21,02	14,38	19,61	5,27	Mechanical	Moderately	8	70/070	Small Problems
20	23,85	7,91	14,83	3,12	Mechanical	Moderately	10	75/010	Small Problems

Table 2. Discontinuity properties of the rocks at each road cut

Road Cut	Discontinuities Dip° / Dip Direction° J1	J2	J3	Large Scale Roughness (RL) J1	J2	J3	Small Scale Roughness (RS) J1	J2	J3	Infill Material J1	J2	J3
1	69/139	40/247	33/319	Wavy	S. Curved	S. Curved	R. Stepped	S. Stepped	S. Stepped	Clay	Clay	Clay
1-F	74/138	38/236	27/320	Wavy	S. Curved	S. Curved	R. Stepped	S. Stepped	S. Stepped	Clay	Clay	Clay
2	20/270	69/100	75/015	S. Curved	S. Curved	S. Curved	S. Planar	S. Planar	S. Planar	Sand	Sand	Sand
2-F	20/270	69/100	75/015	S. Curved	S. Curved	S. Curved	S. Planar	S. Planar	S. Planar	Sand	Sand	Sand
3	16/050	67/180	75/255	Curved	S. Curved	S. Curved	R. Undulating	S. Undulating	S. Undulating	Sand	Sand	Sand
4	5/090	65/250	64/340	S. Curved	S. Curved	S. Curved	S. Stepped	S. Stepped	S. Stepped	Sand	Sand	Sand
5	62/148	80/200	75/012	S. Curved	S. Curved	S. Curved	R. Undulating	R. Undulating	R. Undulating	Sand	Sand	Sand
6	60/125	70/025	50/245	Curved	Curved	Curved	S. Undulating	S. Undulating	S. Undulating	Sand	Sand	Sand
7	70/230	55/340	5/020	S. Wavy	S. Wavy	S. Wavy	R. Undulating	R. Undulating	R. Undulating	Nofill	Nofill	Nofill
8	30/310	70/170	70/070	Curved	Curved	S. Wavy	S. Stepped	S. Stepped	S. Stepped	Sand	Sand	Sand
9	48/145	66/235	30/290	Wavy	Curved	S. Wavy	R. Undulating	S. Undulating	S. Undulating	Sand	Sand	Sand
10	34/354	84/226	50/160	Curved	Curved	Curved	R. Undulating	R. Undulating	R. Undulating	Clay	Clay	Clay
11	36/336	60/150	87/215	S. Wavy	S. Wavy	S. Wavy	R. Undulating	R. Undulating	R. Undulating	Sand	Sand	Sand
12	35/180	55/005	66/298	S. Curved	Curved	S. Curved	S. Stepped	R. Stepped	R. Stepped	Sand	Sand	Sand
13	45/180	84/260	50/310	Curved	S. Wavy	S. Wavy	S. Undulating	S. Undulating	S. Undulating	Sand	Sand	Sand
14	75/130	80/035	84/215	S. Curved	S. Curved	S. Curved	P. Undulating	P. Undulating	P. Undulating	Sand	Sand	Sand
15	55/330	49/145	78/255	Straight	Straight	Straight	S. Planar	S. Planar	S. Planar	Sand	Sand	Sand
16	65/350	60/080	50/165	S. Curved	S. Curved	S. Curved	S. Undulating	S. Undulating	S. Undulating	Clay	Clay	Clay
17	50/350	80/060	50/195	S. Curved	S. Curved	S. Curved	S. Undulating	S. Undulating	S. Undulating	Clay	Clay	Clay
18	75/150	81/262	40/085	S. Curved	S. Wavy	S. Wavy	S. Undulating	S. Undulating	S. Undulating	Sand	Sand	Sand
19	75/130	30/060	80/235	S. Curved	S. Wavy	S. Wavy	S. Undulating	S. Undulating	S. Undulating	Clay	Clay	Clay
20	70/130	15/050	70/220	Curved	Curved	Curved	R. Undulating	R. Undulating	R. Undulating	Clay	Clay	Clay

* S. Wavy: Slightly Wavy, S. Curved: Slightly Curved, R. Stepped: Rough Stepped, S. Stepped: Smooth Stepped, R. Undulating, Rough Undulating, S. Undulating: Smooth Undulating, P. Undulating: Polished Undulating, S. Planar: Smooth Planar

Table 3. SSPC data collection, RRM – SRM properties and stable probabilities for Stop 8

DATA COLLECTION TABLE

Excavation Method (ME)		Intact Rock Strength (IRS)	
Natural/hand-made	1,00	<1.25 MPa	Crumbles in hand
Pneumatic hammer excavation	0,76	1.25-5 MPa	Thin slabs break easy in hand
Pre-splitting/smooth wall blasting	0,99	5-12.5 MPa	Thin slabs broken by heavy hand pressure
Conventional blasting with result:		12.5-50 MPa	Lumps broken by light hammer blows
Good	0,77	50-100 MPa	Lumps broken by heavy hammer blows
Open discontinuities	0,75	100-200 MPa	Lumps only chip by heavy hammer blows
Dislodged blocks	0,72	>200 MPa	Rocks ring on hammer blows
Fractured intact rock	0,67	Weathering degree (WE)	Unweathered 1,00
Crushed intact rock	0,62		Slightly 0,95
Lithology			Moderately 0,90
50% Sandstone / 50% Mudstone			Highly 0,62
			Completely 0,35

Discontinuities (B: Bedding; J: Joint)	J1	J2	J3	Slope	
Dip direction (degrees)	310	170	70	Dip direction (degrees)	215
Dip (degrees)	30	70	70	Dip (degrees)	50
Spacing (DS) (cm)	50	80	40	Slope height (m)	15

Condition of discontinuities			J1	J2	J3	Slope Stability	
Large scale roughness (RL)	Wavy	1,00				Stable	1
	Slightly wavy	0,95			X	Small problem	2
	Curved	0,85	X	X		Large problem	3
	Slightly curved	0,80					
	Straight	0,75					
Small scale roughness (RS)	Rough stepped	0,95					
	Smooth stepped	0,90	X	X	X		
	Polished stepped	0,85					
	Rough undulating	0,80					
	Smooth undulating	0,75					
	Polished undulating	0,70					
	Rough planar	0,65					
	Smooth planar	0,60					
	Polished planar	0,55					
Infill material (IM)	Cemented / cemented infill	1,07					
	No infill - surface staining	1,00					
	Non-softening & sheared material: Coarse	0,95					
	Non-softening & sheared material: Medium	0,90					
	Non-softening & sheared material: Fine	0,85					
	Soft sheared material: Coarse	0,75					
	Soft sheared material: Medium	0,65	X	X	X		
	Soft sheared material: Fine	0,55					
	Gouge < irregularities	0,42					
	Gouge > irregularities	0,17					
	Flowing material	0,05					
Karst (KA)	None	1,00	X	X	X		
	Karst	0,92					

Notes:
1) For infill "gouge>irregularities" and "flowing material" small scale roughness= 0,55
2) If roughness is anisotropic (e.g. Ripple marks, striation, etc.) roughness should be assessed perpendicular and parallel to the roughness and directions noted on this form
3) Non-fitting of discontinuities should be marked in roughness columns.

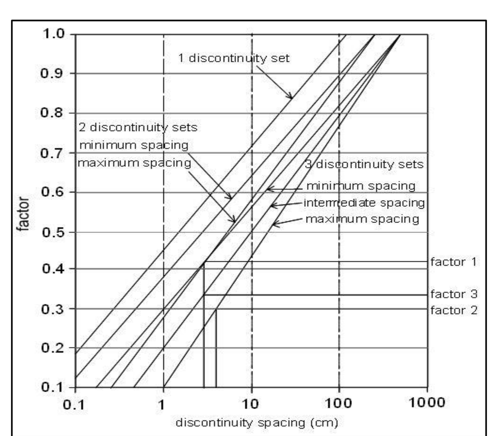
REFERENCE ROCK TABLE

Intact Rock Strength (RIRS)

RIRS = IRS / WE = 13 / 0,90	14,444

Discontinuity Spacing (SPA)

Discontinuities	J1	J2	J3		
Dip direction (degrees)	310	170	70	SPA = factor 1 x factor 2 x factor 3	
Dip (degrees)	30	70	70	SPA = 0,71 x 0,70 x 0,73 = 0,363	
Spacing (m)	50	80	40	Corrected for weathering and method of excavation:	0,531
The spacing parameter (SPA) is calculated based on the three discontinuity sets with the smallest spacings in following figure:				RSPA = SPA / (WE x ME)	
				RSPA = 0,363 / (0,90 x 0,76)	



Condition of discontinuities

Discontinuities	J1	J2	J3	
Large scale roughness (Rl)	0,85	0,85	0,95	
Small scale roughness (Rs)	0,90	0,90	0,90	RTC is the discontinuity condition of a single discontinuity (set) in the reference rock mass corrected for discontinuity weathering. RTC = TC /sqrt(1,452-1,220*e^(-WE))
Infill material (Im)	0,65	0,65	0,65	
Karst (Ka)	1,00	1,00	1,00	
TC = Rl x Rs x Im x Ka	0,497	0,497	0,556	
RTC	0,509	0,509	0,568	

Weighted by spacing: $CD = \dfrac{\frac{TC_1}{DS_1} + \frac{TC_2}{DS_2} + \frac{TC_3}{DS_3}}{\frac{1}{DS_1} + \frac{1}{DS_2} + \frac{1}{DS_3}} =$ 0,523

Corrected by weathering: RCD (with a maximum of 1.0165) = CD/WE = 0,523 / 0,90 = 0,581

Reference unit friction and cohesion (RFRI & FCOH)

ϕ(RRM) = RIRS * 0,2417 + RSPA * 52,12 + RCD * 5,779 = (If RIRS > 132 MPa, then RIRS = 132)	34,53°
coh(RRM) = RIRS * 94,27 + RSPA * 28629 + RCD * 3593 = (If RIRS > 132 MPa, then RIRS = 132)	18,7 kPa

STABILITY TABLE

Method of Excavation (SME)		Weathering (SWE)	
Natural/hand-made	1,00	Unweathered	1,00
Pneumatic hammer excavation	0,76	Slightly	0,95
Pre-splitting/smooth wall blasting	0,99	Moderately	0,90
Conventional blasting with result:		Highly	0,62
Good	0,77	Completely	0,35
Open discontinuities	0,75	**Slope geometry features**	
Dislodged blocks	0,72	Slope dip direction (degrees)	215
Fractured intact rock	0,67	Slope dip (degrees)	50
Crushed intact rock	0,62	Height (m)	15

Orientation-independent stability

Intact Rock Strength (SIRS)		
SIRS = RIRS (from reference rock mass) x SWE (weathering slope) =	14,444 x 0,90	13 MPa
Discontinuity spacing (SSPA)		
SSPA = RSPA x SWE x SME	0,531x0,90x0,76	0,363
Condition of discontinuity (SCD)		
SCD = RCD x SWE =	0,581 x 0,90	0,523
Slope unit friction and cohesion (SFRI & SCOH)		
SFRI = SIRS * 0,2417 + SSPA * 52,12 + SCD * 5,779 = (If RIRS > 132 Mpa, then RIRS =132)		25,08°
SCOH = SIRS * 94,27 + SSPA * 28629 + SCD * 3593 = (If RIRS > 132 Mpa, then RIRS =132)		13,5 kPa
If SFRI < slope dip, maximum possible height (Hmax): Hmax = (1,6x10^-4 x SCOH) x sin(slopedip) x cos(SFRI) / (1 - cos(slopedip - SFRI)) =		16,1 m
Ratios	SFRI / Slope dip	0,502
	Hmax / Hslope	1,073
Stable probability: if SFRI > slope dip, probability = %100, else use the figure for orientation-independent stability:		50%

Orientation-dependent stability

Discontinuities		J1	J2	J3
Dip direction (degrees)		310	170	70
Dip (degrees)		30	70	70
With, Against, Vertical or Equal		A	W	A
AP (degrees)		-3	63	-66
RTC		0,509	0,509	0,568
STC = RTC x sqrt(1,452 - 1,220 x e^(-SWE))		0,497	0,497	0,556
Stable probability:	Sliding	100%	100%	100%
	Toppling	100%	100%	>95%
Stable probability:	>95%			

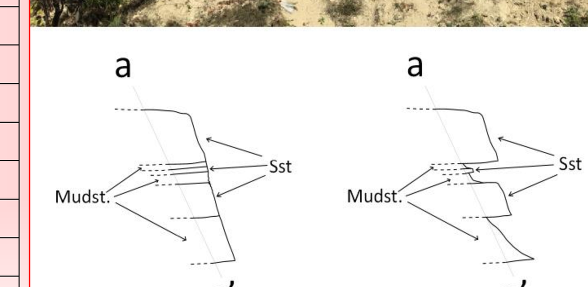
Determine orientation stability:
Calculate AP: β = discontinuity dip, σ = slope dip direction, τ= discontinuity dip direction, δ = σ - τ, AP= arctan(cosδ x tanβ)

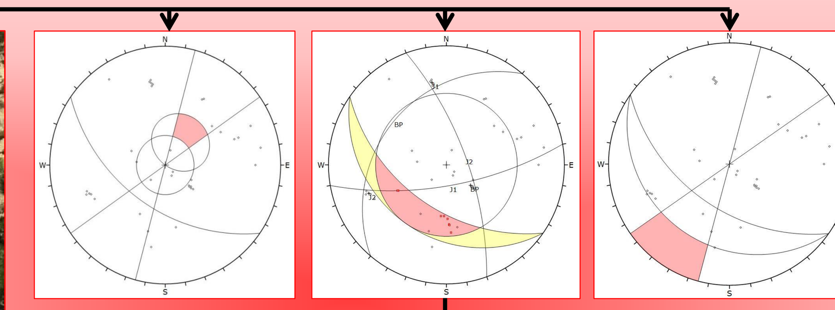
Stability		Sliding	Toppling	Stability		Sliding	Toppling
AP>84° or AP<-84°	Vertical	100%	100%	AP<0° and (-90-AP+slope dip)<0°	Against	100%	100%
(slope dip + 5°) < AP < 84°	With	100%	100%	AP<0° and (-90-AP+slope dip)>0°	Against	100%	Use graph toppling
(slope dip - 5°) < AP < (slope dip + 5°	Equal	100%	100%				
0°< AP < (slope dip - 5°	With	Use graph sliding	100%				
Slope final stable probability	50%						

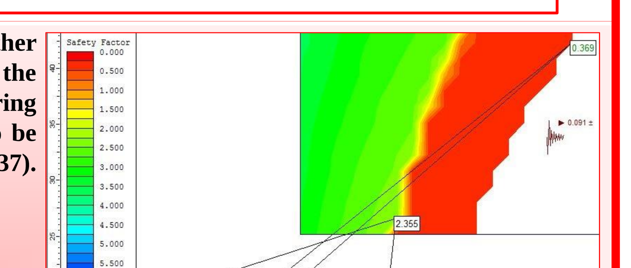
Table 4. Stable probabilities of each road cut

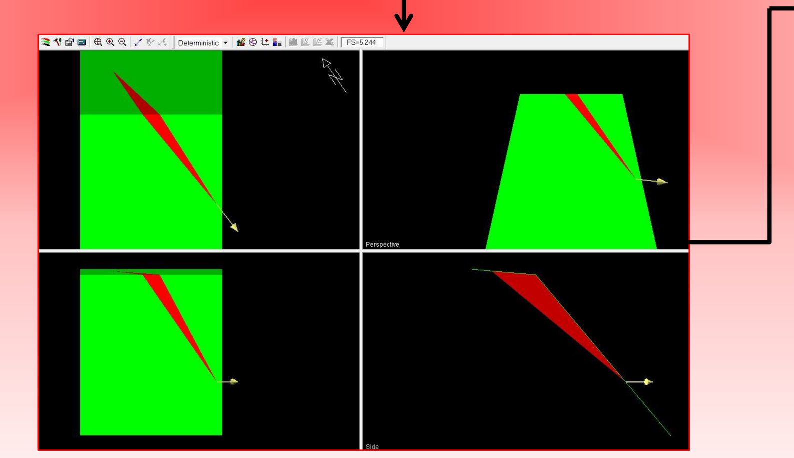
	Mass	Sliding/Toppling
Stop 1	5%	95%
Stop 1 F	5%	95%
Stop 2	5%	100%
Stop 2 F	5%	100%
Stop 3	5%	95%
Stop 4	5%	5%
Stop 5	5%	50%
Stop 6	5%	5%
Stop 7	5%	95%
Stop 8	50%	95%
Stop 9	95%	95%
Stop 10	40%	5%
Stop 11	5%	95%
Stop 12	5%	95%
Stop 13	5%	80%
Stop 14	5%	95%
Stop 15	20%	15%
Stop 16	20%	5%
Stop 17	30%	80%
Stop 18	50%	95%
Stop 19	5%	5%
Stop 20	5%	5%

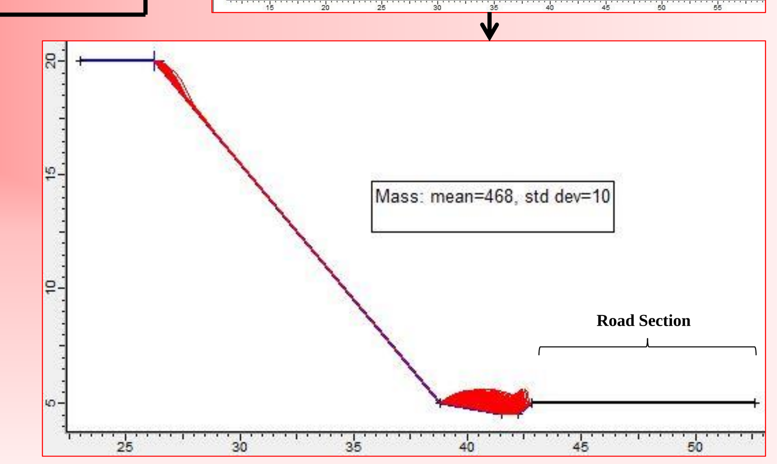
According to SSPC analysis on each road cut, the stable probabilities are shown in Table 4. All road cuts - except Stop 9 - reveal failures either orientation independent (mass) or orientation dependent (Sliding/Toppling) or both of them. In order to understand the type of failure, the procedure given below is introduced as an example for Stop 8. The procedure starts by the possible evolution of Stop 8 due to differential weathering which may cause failures on slope facet. Then it goes on with kinematic analyses. According to kinematic analyses, wedge failure appears to be critical. However, limit equilibrium on wedge reveal FS of 5.2. Then, the overall stability show minimum FS of 2.3 except for the slope facet (0.37). Finally, based on field observations, rockfall analysis is found to be critical for this road cut.











3. DISCUSSIONS & CONCLUSIONS

DISCUSSIONS

Both weathered and relatively fresh samples were gathered from the field as it can be seen from Table 1. Fresh column that is indicated at this table is related to relatively fresh samples compared to the samples taken from the slope facet. The depth of weathered zone on the facets were determined according to these differences.

Considering the strength differences, relatively fresh samples were also used in order to check the reliability of the SSPC system.

REFERENCE ROCK TABLE	
Intact Rock Strength (RIRS)	
RIRS = IRS / WE = ~~13 / 0,90~~	~~14,444~~
	23.29

As it can be seen from the table on the left, relatively fresh value of 23.29 MPa is applied without considering any weathering effect.

Table 5. FS results of each road cut

Stop	Static	Dynamic
1	2,0	1,2
2	2,9	2,7
3	2,3	1,8
4	1,8	1,5
5	2,6	2,4
6	2,1	1,7
7	4,1	3,8
8	2,6	2,3
9	4,8	1,7
10	3,3	3,0
11	2,8	2,6
12	2,1	1,8
13	1,6	1,4
14	2,6	2,3
15	3,2	2,8
16	2,1	1,8
17	2,4	2,1
18	3,4	3,0
19	2,2	2,2
20	1,4	1,4

According to limit equilibrium analyses overall stability of the slopes are satisfying the desired levels (Table 5), which means FS=1.5 for static, FS=1.1. for dynamic conditions.

Basically original method of SSPC system suggests collecting samples and obtaining data from the surface of the slope, which is weathered and disturbed zone most cases. From this data relatively fresh rock properties can be evaluated. It is fortunate that the depth of weathered/disturbed zone was determined in the field which gives better idea about the results of SSPC system. Supportively, according to field observations, it is known that surficial degredation takes place at the study area. Considering this, the results of original method are shown in Figure 4. This shows that SSPC works with a success rate of 95% (coherent with field observations on surficial degradation). Considering the above mentioned 'relatively fresh strength application on SSPC without any weathering effect' success rate decreases to 85% (Figure 5), which is also coherent. The meaning of this 85% success rate is that the SSPC system can evaluate the weathering effect on strength really well.

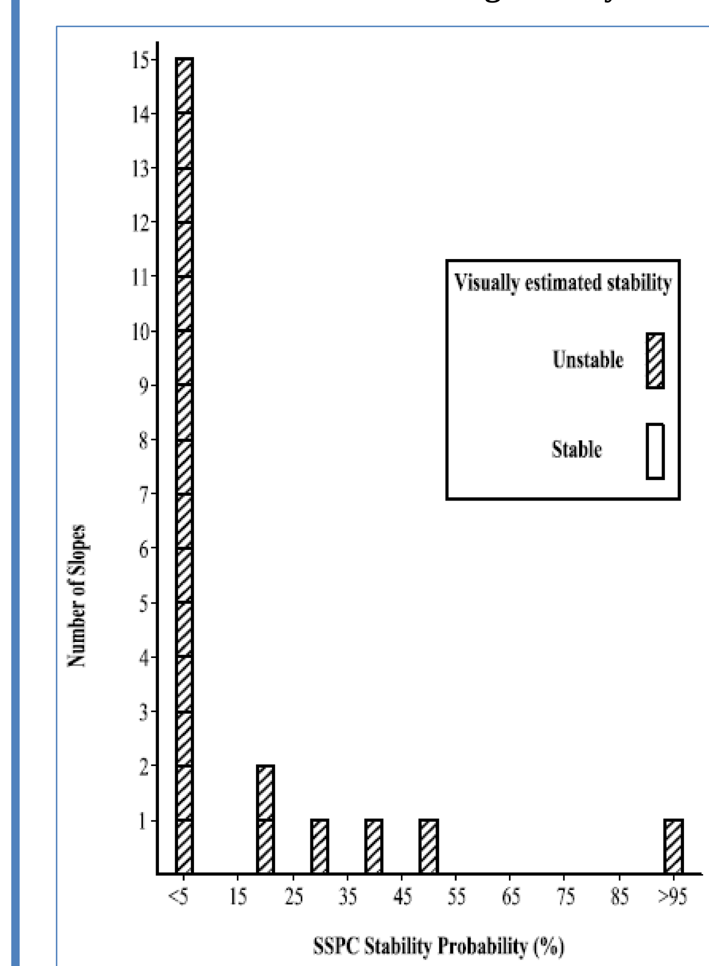


Figure 4. SSPC with weathered strength values.

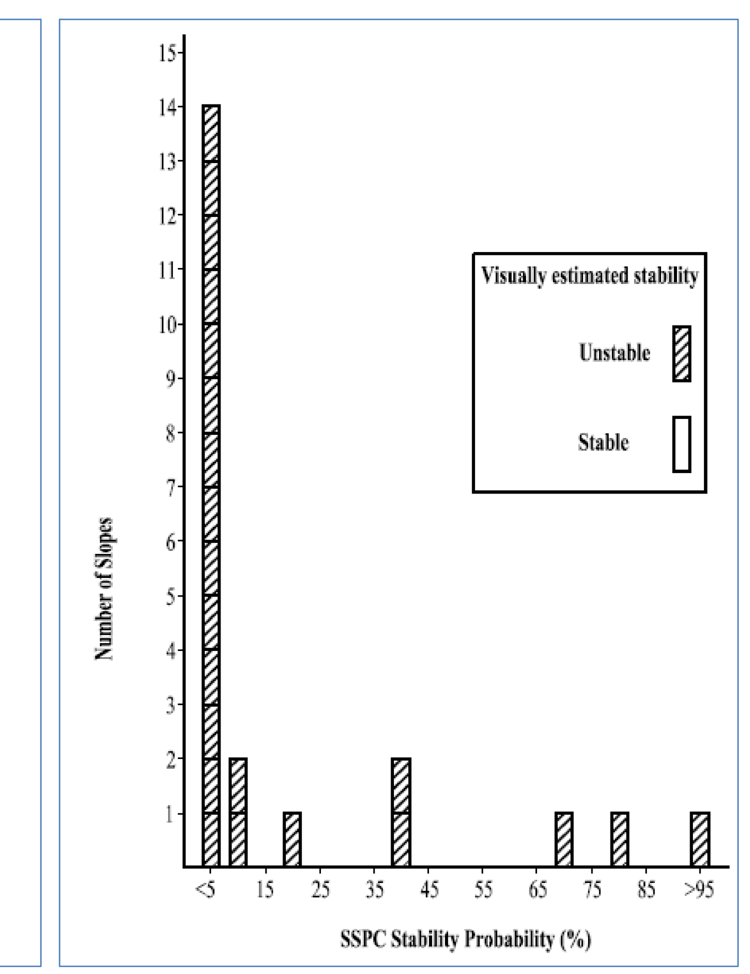


Figure 5. SSPC with relatively fresh strength values.

CONCLUSIONS

Slope Stability Probability Classification (SSPC) system was used to determine stable probabilities in this study. SSPC revealed reliable data for the surface conditions (i.e. weathered/disturbed zones) of the slopes. According to these analyses, SSPC showed 95% success for the surficial failures using original method. SSPC method can be applicable for the surface of the road cuts however some further investigations and analyses need to be done for relatively fresh/undisturbed zones of the cut slopes.

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