Geomechanics and Engineering, *Vol. 13, No. 4 (2017) 571-584*
DOI: https://doi.org/10.12989/gae.2017.13.4.571

Assessment of rock slope stability by slope mass rating (SMR): A case study for the gas flare site in Assalouyeh, South of Iran

Mohammad Azarafza *[1], Haluk Akgün[2a] and Ebrahim Asghari-Kaljahi[3b]

[1]*Department of Geology, University of Isfahan, Isfahan, Iran*
[2]*Department of Geological Engineering, Geotechnology Unit, Middle East Technical University, Ankara, Turkey*
[3]*Department of Earth Sciences, University of Tabriz, Tabriz, Iran*

(*Received April 30, 2016, Revised March 3, 2017, Accepted March 4, 2017)*

Abstract. Slope mass rating (SMR) is commonly used for the geomechanical classification of rock masses in an attempt to evaluate the stability of slopes. SMR is calculated from the $RMR_{89\text{-basic}}$ (basic rock mass rating) and from the characteristic features of discontinuities, and may be applied to slope stability analysis as well as to slope support recommendations.

This study attempts to utilize the SMR classification system for slope stability analysis and to investigate the engineering geological conditions of the slopes and the slope stability analysis of the Gas Flare site in phases 6, 7 and 8 of the South Pars Gas Complex in Assalouyeh, south of Iran. After studying a total of twelve slopes, the results of the SMR classification system indicated that three slope failure modes, namely, wedge, plane and mass failure were possible along the slopes. In addition, the stability analyses conducted by a number of computer programs indicated that three of the slopes were stable, three of the slopes were unstable and the remaining six slopes were categorized as 'needs attention' classes.

Keywords: geomechanics; slope mass rating (SMR); rock mass rating (RMR); Assalouyeh

1. Introduction

Engineering rock mass classification systems have been designed by many researchers around the world and have been widely used in engineering projects. Based on surface or subsurface ground conditions, some of these engineering classifications are: Rock Mass Rating (Bieniawski 1976, 1979, 1989), Mining Rock Mass Rating (Laubscher 1990), Modified-Mining Rock Mass Rating (Haines and Terbrugge 1991), Modified-Rock Mass Rating (Unal 1996), Rock Tunneling Quality Index or Q (Barton *et al.* 1974), TBM Rock Tunnelling Quality Index or Q_{TBM} (Barton 1999), Rock Structure Rating (Singh and Goel 1999), Rock Structure Rating (Wickham *et al.* 1972), Rock Mass Strength (Selby 1980), Slope Mass Rating (Romana *et al.* 2003), Chinese Slope Mass Rating (Chen 1995), Slope Stability Probability Classification (Hack 1998, Hack *et al.* 2003), Geological Strength Index (Marinos *et al.* 2005, Hoek *et al.* 2013), Rock Quality Designation or RQD (Deere *et al.* 1967, Deere and Deere 1988, Deere 1989), Modified Basic

*Corresponding author, Ph.D. Candidate, E-mail: m.azarafza.geotech@gmail.com
[a]Professor, E-mail: hakgun@metu.edu.tr
[b]Associate Professor, E-mail: e-asghari@tabrizu.ac.ir

http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

Rock Mass Rating (Cummings *et al.* 1982, Kendorski *et al.* 1983) and Alternative Rock Mass Classification System (Pantelidis 2010). In these classifications, various parameters and features such as intact rock and discontinuity properties are present. With the help of these classifications, engineering geological and geomechanical conditions may be assessed with a reasonable degree of accuracy and reliability.

Among these classifications, some have been developed for specific purposes. Examples for such specific classifications are the Q system (Barton *et al.* 1974) which has been exclusively used for tunneling, Q_{TBM} (Barton 1999) which has been used for tunnel boring with TBMs and the SMR (Romana *et al.* 2003) which has been used in the classification of rock slopes, where the role of the engineering classification systems for quantifying the geological structures extensively and for designing suitable engineering support systems are highly important.

The SMR is estimated by assigning a specific rating to each parameter under consideration (Pradhan *et al.* 2011, Tomás *et al.* 2007a, 2007b, 2012). The SMR method for slope stability analysis has been applied to understand the stability and probability of failure for natural and engineered slopes (Singh *et al.* 2010, 2013, Trivedi *et al.* 2012, Gupte *et al.* 2013, Vishal *et al.* 2010, 2011, 2015).

2. SMR classification

The SMR classification system was proposed by Romana *et al.* (2003) for the geomechanical classification of rock slopes. It was derived from the $RMR_{89\text{-basic}}$ classification system (Bieniawski 1989) and possesses adjustment factors which rely on the discontinuity conditions, slope orientation and the excavation method.

2.1 $RMR_{89\text{-basic}}$

Based on the latest modification of RMR in 1989 by Bieniawski (1989), the first five parameters of the RMR classification referred herein as the $RMR_{89\text{-basic}}$ classification are used. Eq. (1) gives the five $RMR_{89\text{-basic}}$ parameters

$$RMR_{basic} = UCS + RQD + DS + DC + GW \quad (1)$$

where, UCS is the uniaxial compressive strength of intact rock, RQD is the rock quality designation (RQD), DS is the discontinuity spacing, DC is the discontinuity condition, and GW is the groundwater condition.

The sixth parameter of RMR, which has not been shown herein is the correction based on discontinuity orientation. Instead of this correction, the adjustment factors proposed by Romana *et al.* (2001), (2003), (2005) have been utilized in the paragraphs below in an attempt to account for the correction related to discontinuity orientation in rock slopes by the SMR system.

2.2 Adjustment factors

The adjustment factors named by Romana *et al.* (2001), (2003), (2005) as F_1, F_2, F_3 (as risk parameters) and F_4 are defined as follows:

F_1: A parameter that represents the difference between the dip direction of a discontinuity (α_j) and the dip direction of a rock slope (α_s) with a value of 0.15 to 1.0. This factor is calculated by the following equation

$$F_1 = (1 - \sin\left|\alpha_j - \alpha_s\right|)^2 \quad (2)$$

F_2: A parameter that is dependent on the amount of discontinuity inclination (β_j) with a value of 0.15 to 1.0. This factor is calculated by Eq. (3)

$$F_2 = \tan^2 \beta_j \quad (3)$$

F_3: A parameter that reflects the difference or sum between the dip of slope inclination (β_s) and that of the discontinuity set inclination (β_j). It takes on values ranging from 0 to -60 and is given by Eq. (4)

$$F_3 = \beta_j - \beta_s \quad (4)$$

F_4: A parameter that is related with the excavation method used along the rock slope. It ranges from -8 to +15 where -8 is selected for a poorly blasted slope and +15 for a natural slope.

2.3 SMR

The SMR value is expressed as follows

$$SMR = RMR_{basic} + (F_1 \cdot F_2 \cdot F_3) + F_4 \quad (5)$$

The SMR classification entails 5 categories, 10 classes and 6 suggested support method classes (Romana *et al.* 2003).

3. Case study

In this study, a stability analysis of 12 separate cases of rock slopes that are present at the Gas Flare Site of Phases 6 to 8 of the South Pars Gas Complex (SPGC), located in the latitudes 27°, 32', 35.7" N to 27°, 32', 19.9" N, and the longitudes 52°, 36', 12.1" E to 52°, 35', 20.5" E was performed. The SPGC is located in the southeastern Bushehr province that is approximately 300 kilometers southeast of Bushehr city in the south of Iran (Fig. 1). This site is located in a narrow region at the foothills of the northern coast of the Persian Gulf. The geological map of the study area is shown in Fig. 2, and the locations of the 12 slopes are shown in Fig. 3.

The field observations indicated that the rock masses of the study area consisted of sandstones and conglomerates of the Bakhtiari formation (Pla), clayey marl and marlstone of the Mishan formation (M_m) and carbonated marl and marlstone with sandstones of the Aghajari formation (Mpla) (Azarafza 2013, Azarafza *et al.* 2013, 2014). The marlstone was particularly noticed to be highly susceptible to weathering in moist condition and produced soils that were very sensitive to moisture changes. The geological characterization of the project site is summarized in Table 1.

3.1 Slope stability analysis based on the SMR method

A total of twelve slopes were examined in regards to rock mass quality and the results were

Fig. 1 The location of the study area

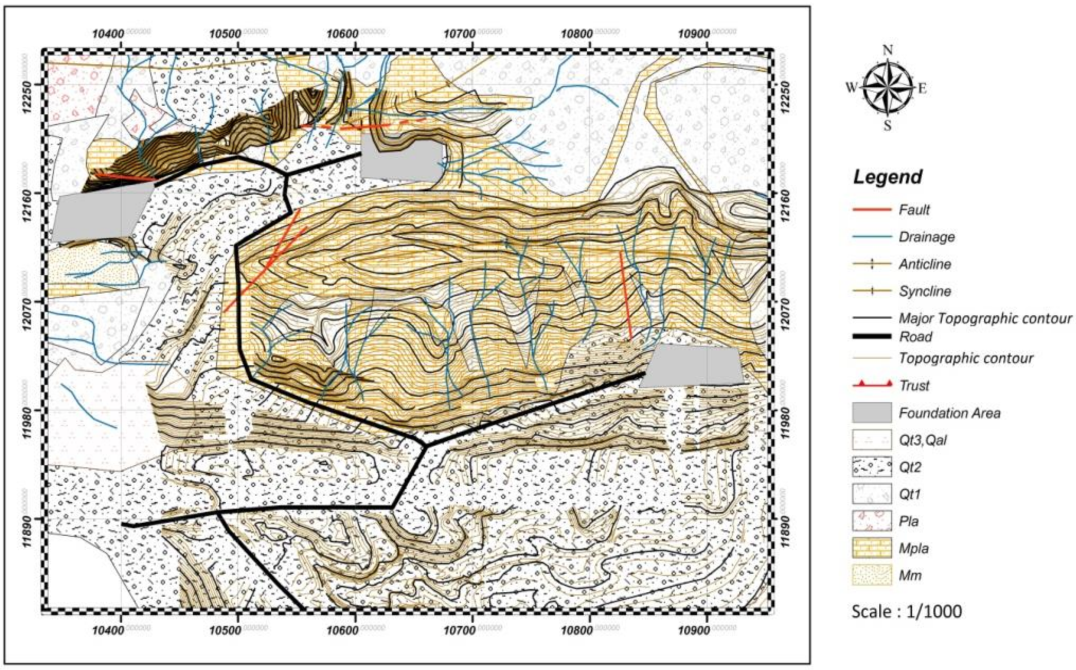

Fig. 2 The geological map of the study area

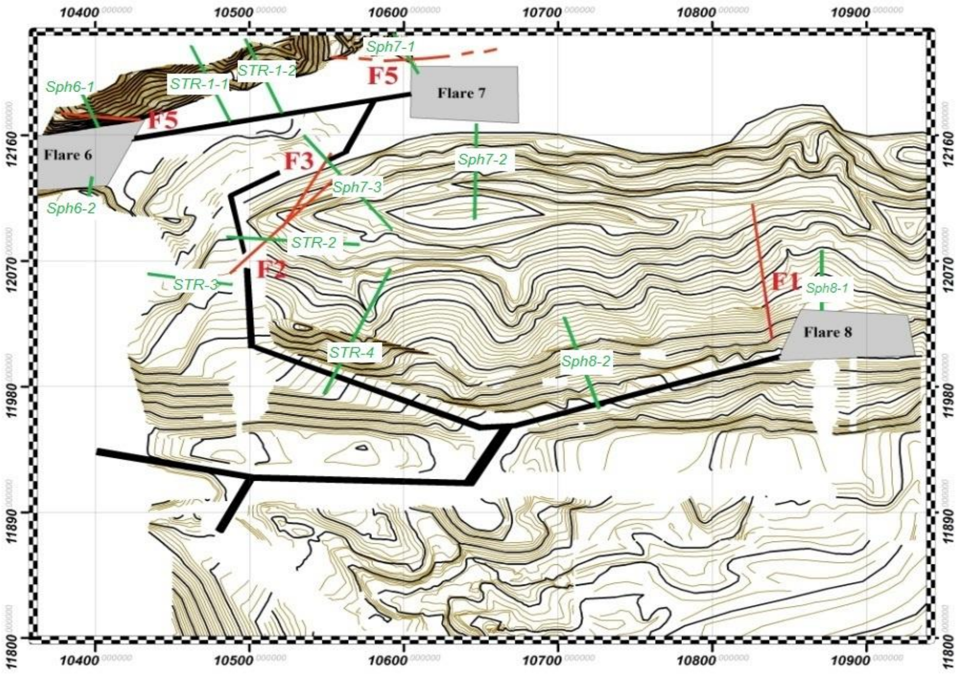

Fig. 3 Location map of the studied slopes

used to assess the stability of the slopes that were located in the study area. According to the field investigations performed in the Gas Flare site, the rock masses of the slopes possess four discontinuity sets of which three of them are joint sets and one of them is a bedding plane set. Fig. 4 shows pictures of the mentioned slopes.

According to the field investigation, it was determined that the most probable mode of rock mass failure was wedge instability. Planar and mass modes of failures were the other two possible modes of failures with lower chances of occurrence as compared to wedge failure. The results are listed in the Tables 2 to 6.

3.2 Stability analysis by computer programs

The SWEDGE (Rocscience 2010a), RocPlane (Rocscience 2010b) and SLIDE (Rocscience 2010c) softwares were used to evaluate and validate the slope stability analysis. The input geomechanical data (based on the Mohr-Coulomb criterion) for the stability analysis is summarized in Table 7. Table 8 presents the results of the slope stability analysis with these softwares.

In this study, the results of the stability analyses of slopes have been classified in three classes based on the factor of safety (FOS) as follows:

•FOS<1 stands for “unstable”,

•1<FOS<1.5 stands for “needs attention” and

•1.5<FOS stands for “stable” slopes, respectively.

The results of modeling with the SWEDGE, SLIDE and RocPlane softwares are shown in Figs. 5 to 7.

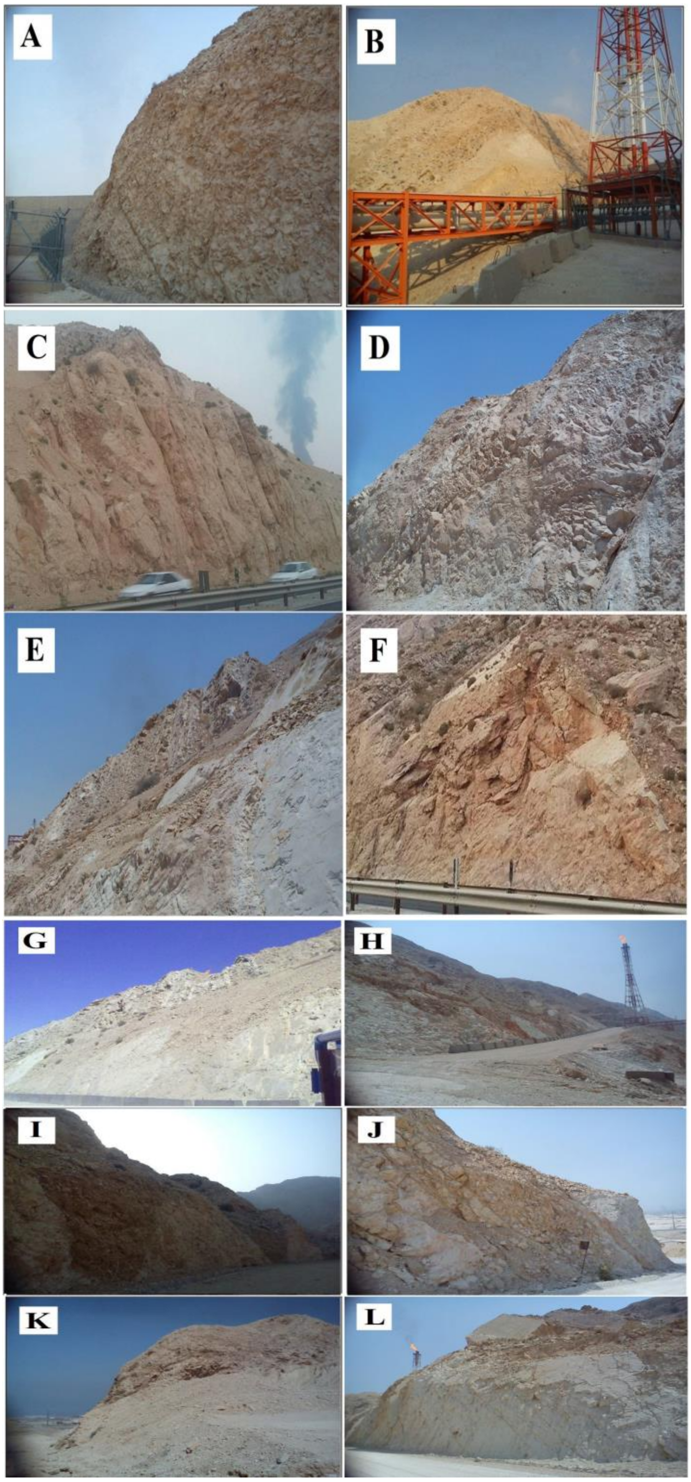

Fig. 4 Views of the studied slopes, (a) S_{Ph6}-01, (b) S_{Ph6}-02, (c) S_{Ph7}-01, (d) S_{Ph7}-02, (e) S_{Ph7}-03, (f) S_{Ph8}-01 (g) S_{Ph8}-02, (h) S_{TR}-01-1, (i) S_{TR}-01-2, (j) S_{TR}-02, (k) S_{TR}-03 and (l) S_{TR}-04

Table 1 Geological characterization of the studied slopes

Slope name	Geological formation	Lithology
S_{Ph6}-01	Aghajari	Red marl with gypsum veins, marl and red to green siltstone
S_{Ph6}-02	Mishan	Gray marl with interlayers of shale
S_{Ph7}-01	Aghajari	Red marl with gypsum veins, marl and red to green siltstone
S_{Ph7}-02	Aghajari	Red marl with gypsum veins, marl and red to green siltstone
S_{Ph7}-03	Aghajari	Red marl with gypsum veins, marl and red to green siltstone
S_{Ph8}-01	Aghajari	Red marl with gypsum veins, marl and red to green siltstone
S_{Ph8}-02	Aghajari	Red marl with gypsum veins, marl and red to green siltstone
S_{TR}-01-1	Aghajari	Red marl with gypsum veins, marl and red to green siltstone
S_{TR}-01-2	Aghajari	Red marl with gypsum veins, marl and red to green siltstone
S_{TR}-02	Aghajari	Red marl with gypsum veins, marl and red to green siltstone
S_{TR}-03	Mishan	Gray marl with interlayers of shale
S_{TR}-04	Aghajari	Red marl with gypsum veins, marl and red to green siltstone

Table 2 Dip and dip directions of the discontinuity sets in the rock masses forming the slopes

Type of discontinuity	Dip (degree)	Dip direction (degree)
Joint set 1	49	161
Joint set 2	50	115
Joint set 3	45	207
Bedding plane	54	323

Table 3 The RMR parameters and RMR ratings of the slopes

Slope Name	UCS	RQD	DS	DC	GW	$RMR_{89\text{-basic}}$
S_{Ph6}-01	2	13	8	10	15	48
S_{Ph6}-02	7	13	8	10	15	53
S_{Ph7}-01	2	8	5	0	15	30
S_{Ph7}-02	2	13	8	10	15	48
S_{Ph7}-03	2	8	5	0	15	30
S_{Ph8}-01	2	8	5	0	15	30
S_{Ph8}-02	7	13	8	10	15	53
S_{TR}-01-1	2	13	8	10	15	48
S_{TR}-01-2	2	13	8	10	15	48
S_{TR}-02	4	13	8	10	15	50
S_{TR}-03	7	13	8	10	15	53
S_{TR}-04	4	13	8	10	15	50

Table 4 The SMR parameters and the SMR ratings/classes of the slopes

Slope Name	F_1	F_2	F_3	F_4	SMR	Class
S_{Ph6}-01	0.70	1.00	0.00	10	58	IIIa
S_{Ph6}-02	0.15	1.00	0.00	10	63	IIb

Table 4 Continued

Slope Name	F_1	F_2	F_3	F_4	SMR	Class
S_{Ph7}-01	0.85	1.00	0.00	10	40	IVa
S_{Ph7}-02	0.70	1.00	0.00	10	58	IIIa
S_{Ph7}-03	0.85	1.00	0.00	10	40	IVa
S_{Ph8}-01	0.85	1.00	0.00	10	40	IVa
S_{Ph8}-02	0.15	1.00	0.00	10	63	IIb
S_{TR}-01-1	0.70	1.00	0.00	10	58	IIIa
S_{TR}-01-2	0.70	1.00	0.00	10	58	IIIa
S_{TR}-02	0.70	1.00	0.00	10	60	IIIa
S_{TR}-03	0.15	1.00	0.00	10	63	IIb
S_{TR}-04	0.70	1.00	0.00	10	60	IIIa

Table 5 Description of SMR classes (Romana *et al.* 2003)

Class	Description	Stability	Failures	Support
Ia Ib	Very good	Completely stable	None	None
IIa IIb	Good	Stable	Some blocks	Occasional
IIIa IIIb	Fair	Partially stable	Some joints	Systematic
IVa IVb	Bad	Unstable	Planar/wedges	Important
Va Vb	Very bad	Completely unstable	Soil like (mass)	Re-excavation

Table 6 Probable failure modes according to the SMR values

Slope name	SMR value	Wedge failure	Plane failure	Mass failure
S_{Ph6}-01	58	Some	-	-
S_{Ph6}-02	63	-	-	None
S_{Ph7}-01	40	Many	-	-
S_{Ph7}-02	58	Some	-	-
S_{Ph7}-03	40	Many	-	-
S_{Ph8}-01	40	Many	-	-
S_{Ph8}-02	63	-	None	-
S_{TR}-01-1	58	-	-	None
S_{TR}-01-2	58	Some	-	-
S_{TR}-02	60	Some	-	-
S_{TR}-03	63	-		None
S_{TR}-04	60	-	None	-

Table 7 The geomechanical properties of the studied rock masses

No.	Lithology (general)	Properties	Mean value
1	Clayey marl	Cohesion (kPa)	0.89
		Friction angle (deg.)	24
		σ_c (MPa)	17.3
		σ_T (MPa)	0.69
		τ (MPa)	2.23
2	Marlstone	Cohesion (kPa)	1.1
		Friction angle (deg.)	35
		σ_c (MPa)	27.6
		σ_T (MPa)	1.10
		τ (MPa)	3.20
3	Carbonated marl	Cohesion (kPa)	1.70
		Friction angle (deg.)	33
		σ_c (MPa)	33.4
		σ_T (MPa)	1.34
		τ (MPa)	3.65

Table 8 The results of the slope stability analysis with computer programs

Slope name	Software	Failure mechanism	FOS	Stability
S_{Ph6}-01	SWEDGE	Wedge	1.43	Needs attention
S_{Ph6}-02	SLIDE	Mass	1.53	Stable
S_{Ph7}-01	SWEDGE	Wedge	0.93	Unstable
S_{Ph7}-02	SWEDGE	Wedge	1.35	Needs attention
S_{Ph7}-03	SWEDGE	Wedge	0.94	Unstable
S_{Ph8}-01	SWEDGE	Wedge	0.91	Unstable
S_{Ph8}-02	RocPlane	Plane	2.42	Stable
S_{TR}-01-1	SLIDE	Mass	1.42	Needs attention
S_{TR}-01-2	SWEDGE	Wedge	1.49	Needs attention
S_{TR}-02	SWEDGE	Wedge	1.01	Needs attention
S_{TR}-03	SLIDE	Mass	1.51	Stable
S_{TR}-04	RocPlane	Plane	1.39	Needs attention

3.3 Stability analysis by the SMR method

When a slope falls within the unstable class, slope stabilization is necessary. The distinctive abilities of the SMR method are to provide recommendation for the slope support systems as illustrated in Fig. 8. Based on the results of the stability analysis by the SMR method and the softwares utilized, the proposed support systems for the slopes in SPGC are presented in Table 9.

Table 9 indicates that three slope failure mechanisms, namely wedge, plane and mass failure are identified at the flare site of which three of the slopes are “stable”, three of the slopes are “unstable” and the rest are placed in the “needs attention” class.

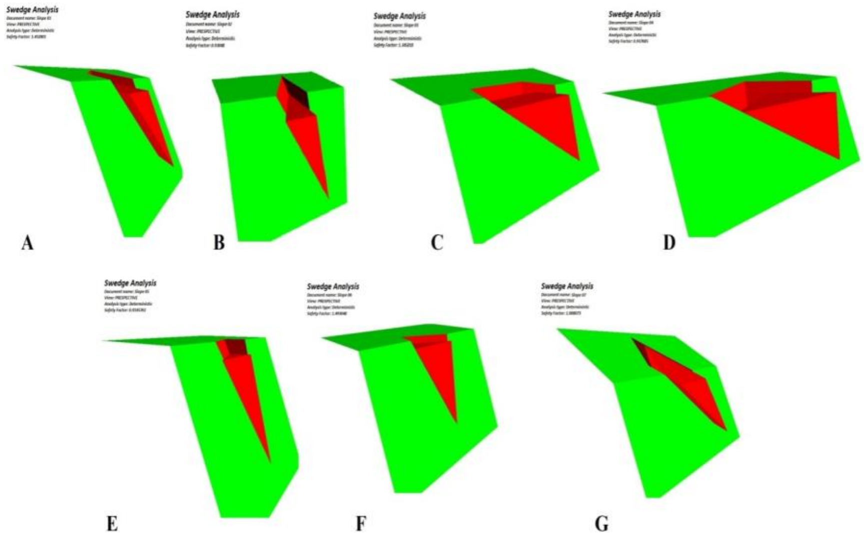

Fig. 5 Results of the stability analysis by the SWEDGE software for slopes, (a) S_{Ph6}-01, (b) S_{Ph7}-01, (c) S_{Ph7}-02, (d) S_{Ph7}-03, (e) S_{Ph8}-01, (f) S_{TR}-01-2 and (g) S_{TR}-02

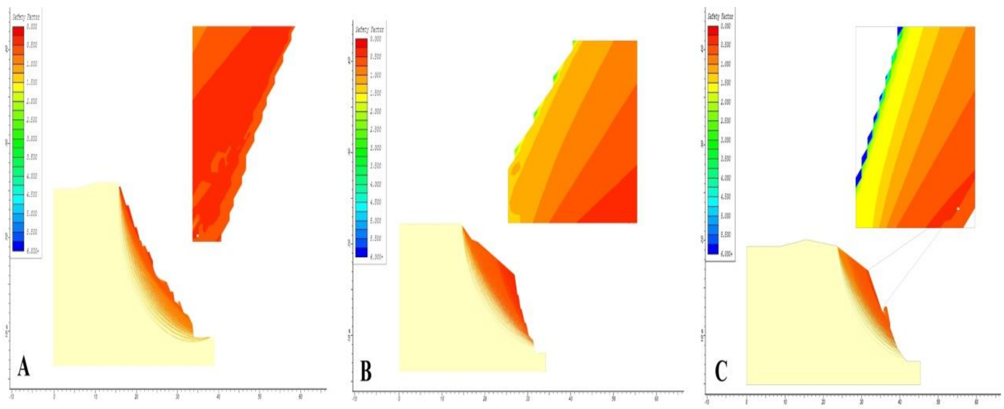

Fig. 6 Results of the stability analysis by the SLIDE software for slopes, (a) S_{Ph6}-02, (b) S_{TR}-01-1 and (c) S_{TR}-03

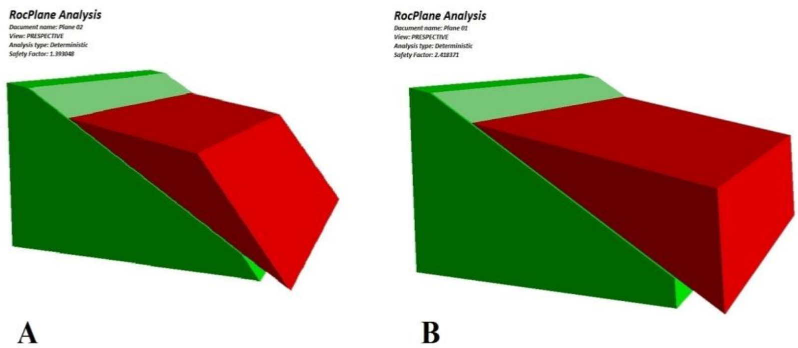

Fig. 7 Results of the stability analysis by RocPlane software for slopes, (a) S_{Ph8}-02 and (b) S_{TR}-04

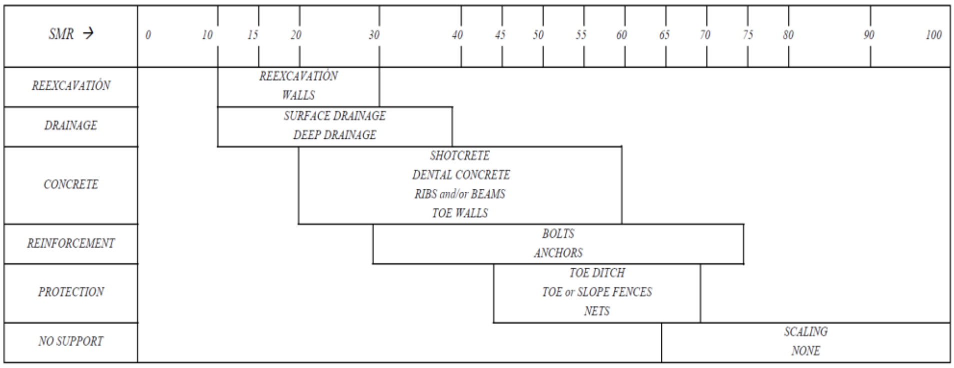

Fig. 8 Suggested support methods for slopes (Romana *et al.* 2003)

Table 9 SMR support recommendations for the studied slopes

Slope name	Failure mechanism	SMR value	Stability	Recommended support
S_{Ph6}-01	Wedge	58	Needs attention	-
S_{Ph6}-02	Mass	63	Stable	-
S_{Ph7}-01	Wedge	40	Unstable	Shotcrete, dental concrete, ribs and/or beams, toe walls or bolts, anchors as necessary
S_{Ph7}-02	Wedge	58	Needs attention	-
S_{Ph7}-03	Wedge	40	Unstable	Shotcrete, dental concrete, ribs and/or beams, toe walls or bolts, anchors as necessary
S_{Ph8}-01	Wedge	40	Unstable	Shotcrete, dental concrete, ribs and/or beams, toe walls or bolts, anchors as necessary
S_{Ph8}-02	Plane	63	Stable	-
S_{TR}-01-1	Mass	58	Needs attention	-
S_{TR}-01-2	Wedge	58	Needs attention	-
S_{TR}-02	Wedge	60	Needs attention	-
S_{TR}-03	Mass	63	Stable	-
S_{TR}-04	Plane	60	Needs attention	-

According to the SMR method, three of the slopes were proposed to be stabilized by shotcrete, dental concrete, ribs and/or beams, toe walls or bolts, anchors as necessary (Table 9).

4. Conclusions

The SMR (slope mass rating) method may be utilized in rock slope stability assessment and analyses. The twelve slopes of the Gas Flare Site in the Assalouyeh region, south of Iran were studied with the aid of the SMR method. The main lithology of the slopes consists of marlstone and sandstone and the rock mass of the slopes possess four sets of discontinuities. The values of the SMR indicated that three failure mechanisms, mainly wedge, plane and mass failure have occurred in the slopes. In addition, according to the stability analysis conducted by the softwares such as SWEDGE, SLIDE and RocPlane, it was determined that three of the slopes were stable, three of the slopes were unstable and the others were categorized as 'needs attention' class. According to the SMR method, three of the slopes were proposed to be stabilized by shotcrete, dental concrete, ribs and/or beams, toe walls or bolts, anchors as necessary.

Acknowledgments

The authors wish to thank the South Pars Gas Complex (SPGC), especially the management of Refinery 4 for giving permission to perform field studies in the phases 6 to 8 of the South Pars Gas flares site.

References

Azarafza, M. (2013), "Geotechnical site investigation gas flares site of phase 6, 7 and 8 in south pars gas complex", M.Sc. Dissertation, University of Yazd, Yazd, Iran.

Azarafza, M., Asghari-Kaljahi, E. and Moshrefy-Far, M.R. (2014), "Numerical modeling and stability analysis of shallow foundations located near slopes (case study: Phase 8 gas flare foundations of south pars gas complex)", *J. Appl. Geol.*, **10**(2), 92-99.

Azarafza, M., Yarahmadi-Bafghi, A.R., Asghari-Kaljahi, E., Bahmannia, G.R. and Moshrefy-Far, M.R. (2013), "Stability analysis of jointed rock slopes using key block method (case study: Gas flare site in 6, 7 and 8 phases of south pars gas complex)", *J. Appl. Geol.*, **9**(3), 169-185.

Barton, N. (1999), "TBM performance estimation in rock using Q_{TBM}", Tunnels and Tunneling International Magazine, September, 30-34.

Barton, N., Lien, R. and Lunde, J. (1974), "Engineering classification of rock masses for the design of tunnel support", *Rock Mech*., **6**(4), 189-236.

Bieniawski, Z.T. (1976), "Rock mass classification in rock engineering", *Proceedings of the Symposium of Exploration for Rock Engineering*, Johannesburg, South Africa, November.

Bieniawski, Z.T. (1979), "The geomechanics classification in rock engineering applications", *Proceedings of the 4th International Congress on Rock Mechanics*, Montreux, Switzerland, September.

Bieniawski, Z.T. (1989), *Engineering Rock Mass Classification*, John Wiley, New York, U.S.A.

Chen, Z. (1995), "Recent developments in slope stability analysis", *Proceedings of the 8th International Congress of Rock Mechanics*, Tokyo, Japan, September.

Cummings, R.A., Kendorski, F.S. and Bieniawski, Z.T. (1982), *Caving Rock Mass Classification and Support Estimation*, US Bureau of Mines Contract Report #J0100103, Engineers International Inc., Chicago, U.S.A.

Deere, D.U. (1989), *Rock Quality Designation (RQD) after 20 Years*, USACE, Contract Report GL-89-1, Waterways Experimental Station, Vicksburg, Mississippi, U.S.A.

Deere, D.U. and Deere, D.W. (1988), "The rock quality designation (RQD) index in practice", *Am. Soc. Test. Mater.*, **984**, 91-101.

Deere, D.U., Hendron, A.J., Patton, F.D. and Cording, E.J. (1967), "Design of surface and near surface construction in rock", *Proceedings of the 8th Symposium on Rock Mechanics*, New York, U.S.A. September.

Gupte, S.S., Singh, R., Vishal, V. and Singh, T.N. (2013), "Detail investigation of stability of in-pit dump slope and its capacity optimization", *J. Earth Sci. Eng.*, **6**(2), 146-159.

Hack, H.R. (1998), *Slope Stability Probability Classification*, ITC Delf Pub., ITC Enschede, the

Netherlands.
Hack, R., Price, D. and Rengers, N.A. (2003), "A new approach to rock slope stability-a probability classification (SSPC)", *Bull. Eng. Geol. Environ.*, **62**(2), 167-184.
Haines, A. and Terbrugge, P.J. (1991), "Preliminary estimation of rock slope stability using rock mass classification system", *Proceedings of the 7th ISRM Congress on Rock Mechanics*, Aachen, Germany, September.
Hoek, E., Carter, T.G. and Diederichs, M.S. (2013), "Quantification of the Geological Strength Index Chart", *Proceedings of the 47th US Rock Mechanics/Geomechanics Symposium*, San Francisco, California, U.S.A., June.
Kendorski, F., Cummings, R., Bieniawski, Z.T. and Skinner, E. (1983), "Rock mass classification for block caving mine drift support", *Proceedings of the 5th International Congress on Rock Mechanics*, Melbourne, Australia, April.
Laubscher, D.H. (1990), "A geomechanical classification system for the rating of rock mass in mine design", *J. S. AFR. I. Min. Metal*, **90**(10), 257-273.
Marinos, V., Marinos, P. and Hoek, E. (2005), "The geological strength index: applications and limitations", *Bull. Eng. Geol. Environ.*, **64**(1), 55-65.
Pantelidis, L. (2010), "An alternative rock mass classification system for rock slopes", *Bull. Eng. Geol. Environ.*, **69**(1), 29-39.
Pradhan, S.P., Vishal, V. and Singh, T.N. (2011), "Stability of slope in an open cast mine in Jharia coalfield, India-a slope mass rating approach", *Min. Eng. J.*, **12**(10), 36-40.
Rocscience (2010a), *SWEDGE-3D Surface Wedge Analysis for Slopes (Version 4.0), Rocscience Inc.*, Toronto, Canada.
Rocscience (2010b), *ROCPLANE-Planar Sliding Stability Analysis for Rock Slopes (Version 2.0), Rocscience Inc.*, Toronto, Canada.
Rocscience (2010c), *SLIDE-2D Limit Equilibrium Analysis of Slope Stability (Version 3.0), Rocscience Inc.*, Toronto, Canada.
Romana, M., Serón, J.B. and Montalar, E. (2001), "La clasificación geomecánica SMR: Aplicación experiencias y validación", *Proceedings of the V Simp Nacional sobre taludes y laderas inestables*, Centro de publications, Secretaria General Técnica. Ministerio de Fomento, CEDEX, Madrid.
Romana, M., Serón, J.B. and Montalar, E. (2003), "SMR geomechanics classification: application, experience and validation", *Proceedings of the 10th Congress of the International Society for Rock Mechanics*, South Africa, Sandton, South Africa, September.
Romana, M., Serón, J.B., Jordá, L. and Vélez, M.I. (2005), "La clasificación geomecánica SMR parataludes: Estado actual, aplicación y experiencia internacional", *Proceedings of the VI Symposium Nacional sobre taludes y laderas inestables*, Valencia, June.
Selby, M.J. (1980), "A rock mass strength classification for geomorphic purposes: With test from Antarctica and New Zealand", *Zeit. Geomorph.*, **24**, 31-51.
Singh, R.P., Dubey, C.S., Singh, S.K., Shukla, D.P., Mishra, B.K., Tajbakhsh, M., Ningthoujam, P.S., Sharma, M. and Singh, N. (2013), "A new slope mass rating in mountainous terrain, Jammu and Kashmir Himalayas: Application of geophysical technique in slope stability studies", *Landsl.*, **10**(3), 255-265.
Singh, B. and Goel, R.K. (1999), *Rock Mass Classification: A Practical Approach in Civil Engineering*, 1st Edition, Elsevier Sciences.
Singh, T.N., Verma, A.K. and Sarkar, K. (2010), "Static and dynamic analysis of a landslide", *Geomat. Natur. Hazard. Risk*, **1**(4), 323-338.
Tomas, R., Delgado, J. and Seron, J.B. (2007a), "Visual sensibility analysis of slope mass rating (SMR) correction parameters using continuous functions", *Proceedings of the 11th Congress of the International Society for Rock Mechanics*, Lisbon, Portugal, July.
Tomas, R., Delgado J. and Seron, J.B. (2007b), "Modification of slope mass rating (SMR) by continuous functions", *J. Rock Mech. Min. Sci.*, **44**(7), 1062-1069.
Tomas, R., Cuenca, A., Cano M. and García-Barba, J. (2012), "A graphical approach for slope mass rating (SMR)", *Eng. Geol.*, **124**, 67-76.

Trivedi, R., Vishal, V., Pradhan, S.P., Singh, T.N. and Jhanwar, J.C. (2012), "Slope stability analysis in limestone mines", *J. Earth Sci. Eng.*, **5**(4), 759-766.

Unal, E. (1996), "Modified rock mass classification: M-RMR system", *Proceedings in Milestone in Rock Engineering*, The Bieniawski Jubilee Collection, Balkema, 203-223.

Vishal, V., Pradhan, S.P. and Singh, T.N. (2010), "Instability analysis of mine slope by finite element method approach", *J. Earth Sci. Eng.*, **3**(6), 11-23.

Vishal, V., Pradhan, S.P. and Singh, T.N. (2011), "Tensile strength of rock under elevated temperatures", *Geotech. Geol. Eng.*, **29**(6), 1127-1133.

Vishal, V., Pradhan, S.P. and Singh, T.N. (2015), "Analysis of stability of slopes in Himalayan terrine along national highway", *Ind. Int. Eng. Geol. Soc. Territ.*, **1**, 511.

Wickham, G.E., Tiedemann, H.R. and Skinner, E.H. (1972), "Support determination based on geologic predictions", *Proceedings of the American Rapid Excavation & Tunneling Conference (RETC)*, American Institute of Mining, Metallurgical and Petroleum Engineers (AIME), Chicago, June.

CC