Proceedings of the XVI ECSMGE
doi:10.1680/ecsmge.60678

Institution of Civil Engineers
publishing

SQI – A quality assessment index for rock slopes

SQI – Indice d'évaluation des talus rocheux

M. Pinheiro[*1], S. Sanches[2], T. Miranda[1], A. Neves[2], J. Tinoco[1], A. Ferreira[2] and A. Gomes Correia[1]

[1] *ISISE, University of Minho, Guimarães, Portugal*
[2] *Ascendi, Matosinhos, Portugal*
[*] *Corresponding Author*

ABSTRACT In this work, an empirical system was developed to obtain a quality index for rock slopes in road infrastructures, named Slope Quality Index (SQI), and it was applied to a set of real slopes. The SQI is supported in nine factors affecting slope stability that contemplate the evaluation of different parameters. Consequently, each factor is classified by degree of importance and influence by assigned weights. These weights were established through a statistical analysis of replies to a survey that was distributed to several experienced professionals in the field. The proposed SQI varies between 1 and 5, corresponding to slopes in very good and very bad condition state, respectively. Besides the advantage linked to a quantitative and qualitative evaluation of slopes, the SQI also allows identifying the most critical factors on the slope stability, which is a fundamental issue for an efficient management of the slope network in the road infrastructure, namely in the planning of conservation and maintenance operations.

RÉSUMÉ Dans ce travail, un système empirique a été développé pour obtenir un indice de qualité pour des talus rocheux dans les infrastructures routières, nommée Indice de la qualité de talus (SQI), et il a été appliqué à un talus réel. L'SQI est pris en charge par neuf facteurs qui influent la stabilité des talus qui envisagent l'évaluation des paramètres différents. Par conséquent, chaque facteur est classé par degré d'importance et d'influence au travers des poids. Ces pondérations ont été établies par une analyse statistique des réponses à un sondage qui a été distribué à plusieurs professionnels du domaine scientifique. L'SQI varie entre 1 et 5, correspondant à talus en très bon et très mauvais état de condition, respectivement. Plus de l'avantage lié à une évaluation quantitative et qualitative des talus, l'SQI permet également d'identifier les facteurs les plus critiques sur la stabilité des talus, ce qui est une question fondamentale pour une gestion efficace du réseau des talus dans l'infrastructure routière, notamment dans la planification de les opérations de conservation et d'entretien.

1 INTRODUCTION

The existing problems in the networks of road infrastructures in most countries are directly or indirectly related to the lack of quality assessment systems that can provide to the management structures tools to assist in the planning of conservation and maintenance operations proactively. As such, there is an urgent necessity to mitigate this problem through a constant search of innovative and effective techniques, allowing optimizing the long-life cycle of these infrastructures. Among all the elements that compose the road network, slopes are the ones that are subjected to less normative rules when compared with bridges, road pavement and electronic equipment for instance.

Nowadays, there is a huge diversity of methods and techniques for slope stability evaluation during the design stage (for instance using limit equilibrium methods, FEM, DEM, probabilistic approaches, etc.). However, methods and techniques for this evaluation during the exploitation stage, i.e. using mainly information of what was really built and its actual state reported from visual inspections, monitoring systems and indirect information (like climatic and seismic zoning), are scarce. In the past years a few quality systems applied to slopes have been proposed but in general they only evaluate some of the factors involved in the slope stability and normally are limited to the analysis of some failure modes (Pierson et al., 1990; Budetta, 2004; Franklin and Senior, 1997; Youssef et al., 2003; Alejano et al., 2008; Romana, 1985). Hence, the mentioned systems are only used to evaluate the rockfall events in the slope instead of a general stability evaluation of rock slopes.

As already referred, despite the existence of index systems that normally consider certain aspects of slope stability, there is still a need for a more complete system that is able to combine a more broad number of factors affecting rock slope stability analysis. Thereby, an innovative system named Slope Quality Index (SQI) that integrates the evaluation of broad range of internal and external factors related to the slope quality and stability was developed (Pinheiro et al., 2014). The system was based on the Liu and Chen (2007) system by adding a larger number of factors and parameters. Each one of these factors have a different weight resulting in SQI values ranging from 1 to 5, translating very good to very bad slope quality conditions, respectively. The SQI can support the development of hazard maps and aid in the decision concerning the intervention plans.

Considering the lack of information in this field, and aiming to increase the reliability of the SQI, some existing and validated systems were embedded in the SQI for the evaluation of some of the factors. For instance the RHRSm (Rock Hazard Rating System modified) is used for the evaluation of rockfall potential. However, the RHRSm was subjected to some adaptations and changes to better suit the purposes of the SQI, resulting in an update, which was called RHRSm2.

2 SLOPE QUALITY INDEX (SQI)

2.1 *Concept*

The main goal of the SQI system is the calculation of an index based on 9 different factors directly or indirectly related to the stability of the slope. As already mentioned, the SQI contemplates other evaluation subsystems to classify some of the 9 factors. To obtain the right value for each factor, a number of parameters have to be firstly evaluated in a range between 1 and 5, the same as the SQI range for the sake of consistency. To obtain the final value of the SQI the factors are then weighted. The range of SQI between 1 and 5 translate very good and very bad conditions, respectively.

After the calculation of the SQI a qualitative scale can be used for a faster and more intuitive interpretation of the slope condition. This approach allows for a qualitative and quantitative slope quality assessment (Table 1).

Table 1. SQI system for rock slopes: qualitative and quantitative classification.

SQI	Slope state
[1; 1.4]	Very Good
[1.5; 2.4]	Good
[2.5; 3.4]	Medium
[3.5; 4.2]	Bad
[4.3; 5]	Very Bad

2.2 *SQI factors and parameter definition*

Terzaghi (1950) presented a classification for the main causes concerning slope instability, which can be grouped in internal, intermediate and external causes. In the development of the SQI a set of internal and external causes were considered.

The factors and parameters of the SQI were set based on the authors' experience and opinions gathered with other experts in rock slope stability. Also important inputs were obtained in a set of documents, namely: i) the reports of Estradas de Portugal (2009) and Technological Research Institute (Carvalho et al., 2007) regarding the risk map for slopes and riverbanks; and ii) Gao et al. (2011), Lindsay et al. (2001), Pantelidis (2009) and Naghadehi et al. (2013) for the necessary parameters to the stability classification of rock slopes. The parameters were gathered in 9 groups named factors as shown in Table 2.

Since this method contemplates a partial rating for each factor, it provides a clear perception of which are the factors/parameters with the highest influence in the quality evaluation. Therefore, the SQI provides a quantitative evaluation of the slope quality and the urgency of an intervention and also in which parameters this intervention should be focus on to provide the highest impact in the slope quality.

In order to obtain a value for each factor, a scale from 1 to 5 was defined for each parameter. The definition of the intervals for each parameter was carried out using existing references adapting some of the recommendations based on the authors' experience, as already referred (Gao et al., 2011; McMillan and Matheson, 1997; Naghadehi et al., 2013; Lindsay et al., 2001; Pantelidis, 2009) and when these references were absent using only the authors' experience validated with discussions with other experts. Nevertheless, these intervals are open for future updating if accumulated experience points out to different values.

Table 2. Factors and parameters considered in the SQI system.

Factor	Parameter
Geometry	Height and inclination of the slope and width of the bench
Geological	Empirical classification systems (RMR, SMR or Q). Type of formation and risk of rockfall (RHRSm2)
Drainage system	Surface and deep drainage system (existence and conservation state)
Inspections	Maintenance and conservation state evaluation
Monitoring	Results from monitoring systems including: inclinometers, topographic marks, piezometers, etc.
Surroundings	Existence of overloads (houses, etc.) and possible vibrations (works, etc.)
Historical	History of accidents on the slope and interventions
Protection	Surface protection (metallic mesh, bolts, etc.) and vegetal cover
Environmental/ Traffic	Seismic zone, precipitation and traffic level

For example, to evaluate the geological factor one of following empirical classification systems for rock masses was used: Rock Mass Rating – RMR (Bieniawski, 1989), Q (Barton et al., 1974), or SMR (Romana, 1985). This factor also includes the rockfall hazard evaluation using the adapted form of the RHRSm (Rock Hazard Rating System), named as RHRSm2.

In the appendix A all the factors, parameters, weights and intervals of values necessary to calculate the SQI are presented.

The level of information existing in a slope network is variable. Thus, three SQI subsystems were developed taken into account different levels of available information. Obviously, the system will be more robust and reliable if the available information is richer. Therefore, the three different subsystems comprise: 1) Complete system - considers the existence of all the information concerning the rock slope; 2) Intermediate system - the information concerning the monitoring factor is not considered; 3) Simple system - the information concerning monitoring, historical and visual inspections factors are not considered.

For the simpler systems, the weights of the missing factors are proportionally distributed by the remaining ones and the calculation of the SQI is carried out as previously described.

2.3 Factor Weight definition

Since the influence of each factor in the slope stability evaluation is not the same, each factor was weighted by a coefficient that measures its importance and influence degree. To define those weights a survey was developed and distributed to a group of professionals that work in the slope stability topic and with different profiles, from academics to practitioners. In this survey the professionals had to compare the relative importance of the factors in a scale from 1 to 9, with the lowest value meaning the same importance and 9 a extremely higher importance of the factor at stake. The importance degrees were defined using the Analytic Hierarchy Process method, proposed by Saaty (1980).

The professionals were grouped in three categories based on their level of knowledge concerning slope stability, namely: Expert, High knowledge and Regular knowledge. As such, this division allowed, not only to weigh the answers according to the level of knowledge, but also to analyze the differences in the answers between each level.

Thirty-one answers were obtained from the survey showing a great variety of responses from the 3 levels of knowledge. To analyze the results the calculation methodology proposed by Liu and Chen (2007) was used. To obtain the final weight values three different scenarios were considered: 1) same importance in the answers for the different knowledge levels; 2) increase in 20% the importance of the answers from the Expert level and decrease in the same proportion the answers from the professionals with Regular level of knowledge; 3) the same as in the previous case but considering a 30%

variation. In this work the weights given in scenario 2 were adopted.

Different weights were also assign for the different parameters within the factors. These values were directly assigned by the authors based on their experience and discussion with other experts. The importance of all the factors and parameters regarding the SQI are presented in appendix A (the values placed next each name of factor/parameter).

3 SQI APPLICATION

The SQI system was applied to a randomly chosen slope located in the Beira Alta e Litoral highway Concession managed by Ascendi and located in the west coast of Portugal. In this slope there were no monitoring data therefore the intermediate system was applied. The weight of this factor (W=0.11) was proportionally distributed by the remaining eight factors. Furthermore, the information concerning the empirical systems (RMR, Q or SMR) was also absent, so their weights were also distributed by the remaining parameters of the geological factor. Given the existing information it was possible to apply the RHRSm2 system to the slope.

To validate the SQI result, an evaluation was performed by a group of professionals from the Expert level of knowledge. It was asked to this group to assign a quality to the slope in a range from 1 to 5 after a visual inspection. The group of experts assigned this value without knowing the result of the SQI and the same value was obtained with both evaluations. The results of the SQI parameters are presented in Table 3 and a value of 3.27 was obtained meaning a slope with medium quality.

Figure 1. General view of the selected slope.

Table 3. SQI parameters results for selected slope.

Factor	Rating results
Geometry	0.74
Geological	0.58
Drainage system	0.5
Inspections	0.52
Monitoring	0.0
Surroundings	0.08
History	0.15
Protection	0.43
Environmental/Traffic	0.27
TOTAL	**3.27**

4 CONCLUSIONS

In this paper a new system for rock slope stability analysis during the exploitation stage called Slope Quality Index (SQI) system was presented. It allows the calculation of an index that considers the evaluation of 9 different factors. Within these factors a number of parameters have also to be assessed with scores ranging from 1 to 5. To translate different levels of influence of the factors and parameters in rock slope stability weights were assigned to each one of them. The parameters weights were quantified according to the authors' experience whereas for the factor weights a more complex methodology was adopted, involving a survey that was distributed to professionals that work in this field of study.

The SQI scale varies from 1 to 5, meaning respectively very good and very bad slope quality. Thereby, it was defined that for a score equal or higher than 3, a security alert for the slope should be activated.

The SQI was applied to a slope and the results were compared to an evaluation made by a panel of experts. The SQI system provides a realistic overview on the slope condition and can surely be used as a quantitative and qualitative evaluation system for slopes in exploitation phase. Moreover, the SQI also allows the identification of the most critical and important factors contributing for the overall condition of the slope, which provides an important aid in the decision making process and planning of interventions.

In conclusion, the SQI system has a significant interest for companies and institutions that have to manage a great number of slopes in the scope of transportation infrastructures since it provides a realistic evaluation of slopes that can be carried out based on different levels of available data.

ACKNOWLEDGEMENT

The authors would like to thank AdI – Innovation Agency, for the financial support awarded through POFC program, for the R&D project SustIMS – Sustainable Infrastructure Management Systems (FCOMP-01-0202-FEDER-023113).

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APPENDIX A

The rock types were set based on the groups defined by Naghadedhi et al. (2013) and Hoek et al. (1995) and can be modified and adapted according to the typical types of formations existing in situ where the SQI would be implemented.

Table A.1. Rock types definition.

Table A.2. SQI System.

Type I	Type II	Type III	Type IV	Type V
Metamorphic: Gneiss, quartzite, and Anfibolite Migmatite; igneous: Granite, Granodiorite, Diorite and Gabbro	Metamorphic: Cornean; Sedimentary: Conglomerate; Igneous: Andesite, Norite, Obsidian and Dolerite	Sedimentary: sandstone and greywacke; Igneous: Basalt, Tuff, Brechia, Dacite and rhyolite	Metamorphic: Shale, Milonite marble; Sedimentary: Gypsum and Anhydrite	Metamorphic: Phyllite and Slate; Sedimentary: Limestone, Siltstone and mudstone

Factors	*Parameters*		*Categories and Ratings*				
Geometry *0.17*	**Slope Height (m)** (*0.5*)		<10	10-20	20-30	30-40	>40
			Very low	Low	Medium	High	Very high
	Rating		1	2	3	4	5
	Slope angle (º) (*0.35*)		< 30	30-40	41-50	51-60	> 60
			Very gradual	Gradual	Medium	Inclined	Too inclined
	Rating		1	2	3	4	5
	Bench angle (*0.15*)		Correct[1]	Incorrect[1]	-	-	-
	Rating		1-2	4-5	-	-	-
	Bench width (m) (*0.25*)		0-1	1-2	2-3	3-4	>4
	Rating		5	4	3	2	1
Geological *0.14*	**Formation type** (*0.50*)	**Type[A.1]** (*0.40*)	I	II	III	IV	V
		Rating	1	2	3	4	5
		Weathering degree (*0.30*)	1	2	3	4	5
		Rating	1	2	3	4	5
		Faults[2](*0.30*)	Exist	None exist	-	-	-
		Rating	4-5	1-2	-	-	-
	Blocks (*0.20*)	**RHRSm2** (1.00)	<51	51-153	153-333	333-459	>459
		Rating	1	2	3	4	5
	Empirical systems (Only one system: Q, RMR or SMR) (*0.30*)	**Q** (*0.33*)	40-1000	10-40	4-10	1-4	0.001-1
		Rating	1	2	3	4	5
		RMR (*0.34*)	100-81	80-61	60-41	40-21	20-0
		Rating	1	2	3	4	5
		SMR (*0.33*)	100-81	80-61	60-41	40-21	20-0
		Rating	1	2	3	4	5
Drainage system *0.11*	**Surface drainage** *0.60*	**Conservation state** (*0,35*)	Very good	Good	Medium	Bad	Very bad
		Rating	1	2	3	4	5
		Maintenance state (*0.45*)	Good	Medium	Bad	-	-
		Rating	1	2	3	-	-
		Presence (*0.20*)	Yes	No	-	-	-
		Rating	1-2	4-5	-	-	-
	Deep drainage (0.20)	**Presence** (*1.00*)	Yes	No	-	-	-
		Rating	1-2	4-5	-	-	-
	Bench Drainage (*0.20*)		Yes	No	-	-	-
	Rating		1-2	4-5	-	-	-
Visual inspections *0.13*	**Conservation state** (*0.60*)	**Classification**	Very good	Good	Medium	Bad	Very bad
		Rating	1	2	3	4	5
	Maintenance state (*0.40*)	**Classification**	Good	Medium	Bad	-	-
		Rating	1	2	3	-	-
Monitoring[3] *0.11*		-	-	-	-	-	-
Historical *0.07*	**Accidents on the slope[4]** *0.70*	**Rockfall** (*0.25*)	None	Inactive	Some	Active	Very active
		Rating	1	2	3	4	5
		Plane (*0.25*)	None	Inactive	Some	Active	Very active
		Rating	1	2	3	4	5
		Wedge (*0.25*)	None	Inactive	Some	Active	Very active
		Rating	1	2	3	4	5
		Circular (*0.25*)	None	Inactive	Some	Active	Very active
		Rating	1	2	3	4	5
	Interventions (*0.30*)		Level 3	Level 2	Level 1	-	-
	Rating		1-2	3	4-5	-	-
Environmental/Traffic *0.08*	**Seismic zone** *0.30*	**Type 2** (*0.60*)	2.1	2.2	2.3	2.4	2.5
		Rating	5	4	3	2	1
		Type 1 (*0.40*)	1.1	1.2	1.3	1.4	1.5-1.6
		Rating	5	4	3	2	1
	Annual rainfall (mm) (*0,50*)		<100	100-500	500-1000	1000-2000	>2000
	Rating		1	2	3	4	5
	Traffic *0.20*	**Max. speed (Km/h)** (*0.50*)	50 – 60	60 – 70	70 – 90	90 – 100	100 - 120
		Rating	1	2	3	4	5
		Av. daily traffic (*0.50*)	< 18000	1800 – 1900	1900 – 2000	2000 - 2200	> 22000
		Rating	1	2	3	4	5
Protection *0.10*	**Surface protection** (*0.80*)		<25%	[25%-50%[	50%	]50%-75%]	]75%-100%]
	Rating		5	4	3	2	1
	Vegetal cover (*0.20*)		Non exist	Punctual	Uniform	-	-
	Rating		5	4-3	1-2	-	-
Surroundings *0.09*	**Overload** (*0.60*)		Yes	No	-	-	-
	Rating		5	1	-	-	-
	Surrounding vibrations (*0.40*)		Yes	No			
	Rating		5	1	-	-	-

[1]For a Correct rating the angle of the bench should be opposed to the slope angle. [2]This parameter should only be scored if faults present an unfavourable orientation for slope stability. [3]The monitoring factor does not present the range values for each parameter because these limits are not yet totally defined. [4]None: no registered accident; Inactive: small/medium scale accident in a 10 years time space; Some: small/medium scale accident in a 5 years time space; Active: small/medium scale accident in a 3 years time space and large accidents in a 1 year time space; Very Active: small, medium and large scale accidents in a 1 year time space.