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Validation of empirical rock mass classification systems for rock slopes

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ABSTRACT

Many classification systems have been proposed in the literature to identify the state of stability of rock slopes. Most of these classification systems involve factors relevant to the general condition of the rock mass, for example, intact rock strength (UCS), geometry and condition of discontinuities, and groundwater condition. Such factors represent the basic part of most of the classification systems, which refer to the well-known Bieniawski's Rock Mass Rating or RMR system. However, these factors were initially developed for underground excavations. Therefore, these classification systems have been subjected to many criticisms and were questioned for their suitability for rock slopes.

In this paper, some of the common classification systems for rock slopes are used to identify their suitability for rock cuts. Twenty two sites of rock cuts in mountainous roads affected by heavy rainfall in the southwestern part of Saudi Arabia have been selected as case studies, and four empirical methods are examined for these case studies. The selected methods are Slope Mass Rating or SMR (Romana, 1985), continuous SMR (Tomás, 2007), Chinese SMR (Chen, 1995), and a graphical SMR (Romana, 2012). The stability conditions for each site have been determined by each of these methods and a comparison between the results is made for the case of plane failure mode. It is shown that some of the empirical methods are not applicable such as Chinese SMR (for slopes less than 80 m high), and the graphical SMR method when the slope angle is more than 80°.

KEYWORDS: Empirical methods; SMR; graphical SMR; continuous SMR

1. INTRODUCTION

Rock slope failure is one of the most common problems in roads, highways, and railways constructed in mountainous and rugged areas. This has the potential to cause road infrastructure and property damage, injuries, and even fatalities.

Different techniques have been proposed to address rock slope instability. One of these methods is rock mass classification systems (empirical methods) representing an important tool to assess the engineering behaviour of the rock mass. Empirical relations between rock mass properties and the behaviour of the rock mass in relation to a particular engineering application are combined to give a method of designing the rock structure. Over the last few decades the rock mass classification systems have been commonly used to assess the stability of rock slopes and identify those of high risk of instability (Pantelidis, 2009).

Rock mass classification procedures (empirical methods) were initially developed for underground excavations as a means to evaluate discontinuous rock mass. The classification systems were developed primarily empirically by establishing the parameters of importance, giving each parameter a numerical value and a weighting factor. This led, via empirical formulae, to final rating for a rock mass. The final rating is related to the stability of the underground excavation used for the development of the classification system (Hack et al., 2003).

In this paper, rock mass classification systems are discussed in terms of their suitability and validity for the analysis of rock slope stability. Some of these systems are addressed in this study. These are: Slope Mass Rating or SMR (Romana, 1985), Chinese Slope Mass Rating (Chen, 1995), Continuous Slope Mass Rating (Tomás, 2007), Graphical Slope Mass Rating (Tomás, 2012).

Twenty two sites have been selected in the southern-west of Saudi Arabia (Figure 1), in order to examine these four classification systems for their suitability and applicability to rock slope stability assessment. These empirical methods are discussed in the following section.

2. CLASSIFICATION SYSTEMS FOR ROCK SLOPE ASSESSMENT

A number of classification systems have been adopted for assessing the rock mass and the stability conditions of rock slopes. These classification systems are described below. The Rock Mass Rating (RMR) system developed by Bieniawski (1973-1989) is considered the basis of all empirical systems. RMR system was first developed to analyze the rock mass condition in tunnels; it was later modified to analyze slopes and foundations. The RMR value is computed

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by adding ratings values of five parameters according to Bieniawski (1989). These are: 1) Strength of intact rock, 2) Rock quality designation (RQD), 3) Spacing of discontinuities, 4) Condition of discontinuities, and 5) Water inflow through discontinuities. These five parameters represent the basic RMR. Bieniawski added a parameter in 1979 to the basic RMR system as an adjustment for discontinuity orientation (Aksoy, 2008). The adjustment parameter for discontinuity orientation was derived for tunnels and dam foundations but not for slopes. Bieniawski (1989) recommended the use of Slope Mass Rating (Romana, 1985), for determining the value of the discontinuity orientation. The RMR system gives a value which ranges between 0 and 100.

2.1 Slope Mass Rating (SMR)

Slope Mass Rating system was proposed by Romana in 1985 as a tool for the preliminary assessment of slope stability. SMR system provides a number of simple rules about the instability modes and required support measures. SMR classification is based on the Rock Mass Rating by Bieniawski (1979). Two kinds of structural failure modes are considered in this classification. These are planar and toppling failures.

The SMR value is obtained from the basic RMR score (ignoring the discontinuity orientation factor from RMR) by subtracting a factorial adjustment factors depending on the joint-slope relationship and adding a factor depending on the method of excavation as expressed in the following equation:

$SMR = RMR_{basic} + (F_1 \times F_2 \times F_3) + F_4$. (1)

In the above, RMR is the basic score of the rock mass rating. F1 is an adjustment factor, which depends on parallelism between joints and slope face strike. It ranges from 1 when near parallel, to 0.15 when angle between strikes is 30 degree (Table 1). F2 is an adjustment factor that refers to joint dip angle in the planar mode of failure. It varies from 1 for joints dipping more than 45° to 0.15 for joints dipping less than 20°. F3 is an adjustment factor that reflects the relationship between the slope face and joint dip. F3 ranges from 0 when the angle is more than 10 degree “Very favorable”, to -60 when the angle is less than -10 degree “Very Unfavorable”. F4 is an adjustment factor that depends on the method of excavation. The values are selected empirically as follows:

1) Natural slope “more stable” F4=+15, 2) Pre-splitting F4=+10, 3) Smooth blasting F4= +8, 4) Normal blasting F4=0. 5. Deficient blasting “damage stability” F4= -8.

The SMR classification was modified by Anbalagan et al. (1992), where the wedge failure was added to the system. Both planar and wedge failures are considered as different cases in the modified SMR, but in this paper this modified SMR will not be discussed and only the plane failure will be addressed.

2.2 Chinese Slope Mass Rating (CSMR)

The Chinese slope mass rating (CSMR) was proposed by Chen in 1995, where two coefficients were added to the Romana’s system (SMR). These two coefficients are the slope height factor (ζ), and the discontinuity factor (λ), as shown in the following equation.

$CSMR = (\zeta \times RMR_{basic}) + [\lambda \times F_1 \times F_2 \times F_3 + F_4]$..(2)

ζ can be defined from the following relationship

$\zeta = 0.57 + 0.43 \times 80/H$ ..(3)

H is the slope height in meter

λ is based on the discontinuity type as follows:

λ=1 for faults, long weak seams filled with clay

= 0.8 to 0.9 for bedding planes, large scale joints with gauge, and

= 0.7 for joints, tightly interlocked bedding planes. Regarding the slope height the Chinese slope mass rating is applicable for slope height more than 80m and any slope equal to 80m or below the equation will be used without the factor of slope height.

2.3 Continuous Slope Mass Rating (CoSMR)

This system uses a continuous function for SMR adjustment factors. It was proposed by Tomás et al. (2007). In this system continuous functions for F1, F2, and F3 correction parameters have been developed.

The proposed F1, F2, and F3 continuous functions that best fit discrete values of Romana’s system are expressed as:

$F_1 = \frac{16}{25} - \frac{3}{500}\arctan\left(\frac{1}{10}(|A| - 17)\right)$ ..(4)

$|A| = |\alpha_j - \alpha_s|$ $for\ planar\ failure$

$= |\alpha_j - \alpha_s - 180|$ $for\ toppling\ failure$

$= |\alpha_i - \alpha_s|$ $for\ wedge\ failure$

Where α_j, α_s and α_i are the joint dip direction, slope dip direction, and the trend of the line of intersection of two planes.

$F_2 = \frac{9}{16} + \frac{1}{195}\arctan\left(\frac{17}{100}B - 5\right)$..(5)

Where B is the dip angle of the joint for planar and toppling failure modes(β_j), and the plunge of the line of intersection of two planes for wedge failure mode(β_i).

B is arctangent function expressed in degree.

$F_3 = -30 + \frac{1}{3}\arctan C$ ..(6)

The relationship (6) is used for slopes with planar and wedge failures.

$F_3 = -13 - \frac{1}{7}\arctan(C - 120)$..(7)

The relationship (7) is used for slopes with toppling failure.

Where C is the absolute difference in angle between the joint dip and slope dip in case of planar failure mode$|\beta_j - \beta_s|$, and between the plunge of the line of intersection of two planes and the dip of the slope $|\beta_i - \beta_s|$ for the wedge failure mode, and the sum of the two dip angles of the joint and slope for the mode of toppling failure$|\beta_j + \beta_s|$.

2.4 Graphical Slope Mass Rating (GSMR)

A graphical method was proposed by Tomás et al. (2012), where he designed new Stereo plots based on the planar, wedge, and toppling failures to determine the rating values of the slope mass rating correction factors. The two correction factors for joint direction and dip; F1 and F2, respectively, are grouped in one term (ψ). The projection of great circles for main joint sets, as well as the slope face are laid on these proposed stereo plots in accordance with the type of failure. Subsequently, the rating values of FI, F2, and F3 are determined for each kind of failure. Then the equation of the SMR is as follows:

$$SMR = RMR_{basic} + (\psi \times F_3) + F_4 \text{ ..(8)}$$

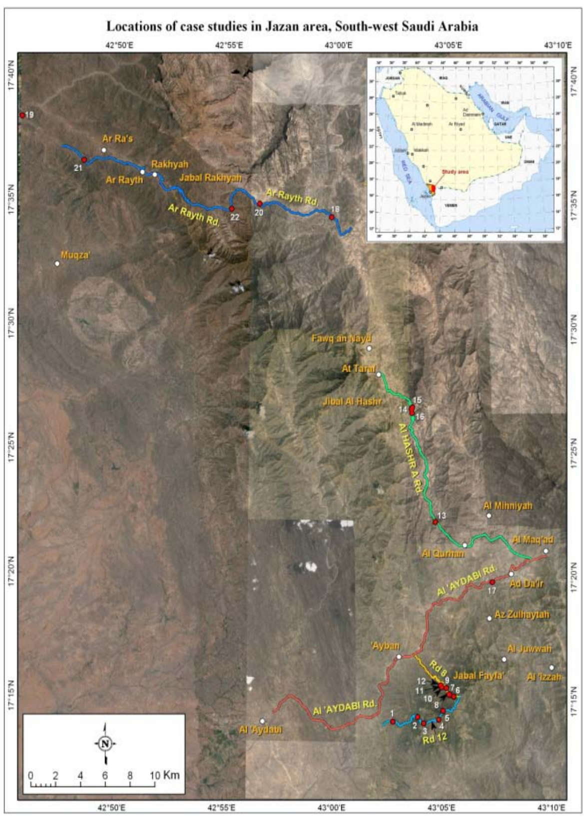

Figure 1: Locations of case studies in Saudi Arabia.

3. LOCATION OF THE STUDY AREA

The study area is located in Jazan region in the south-western part of Saudi Arabia (Figure 1). It is located between Lat. 16° and 18° N, and long between 42° and 44° E.

Twenty-two sites of rock cuts along the mountainous roads in the study area have been selected. These case studies were chosen on the basis of slopes with structurally controlled failure (Figure 2), slopes with stress-controlled failure (Figure 3), and stable slopes. A field trip has been done to identify these sites and collect necessary geological and geotechnical data from each site.

These sites are distributed as follows: Five sites along road 12, seven sites on road 8, four sites on Al Hasher road and five sites along Al Raith road and 1 site on Al 'Aydabi road (Figure 1).

Figure 2: Site #1 along road 12 represents an example of structurally controlled failure.

Figure 3: Site # 21 on Al-Raith road exposed to failure due to stress controlled factor (completely weathered).

4. DISCUSSION OF RESULTS

The results of the RMR-system indicate that the rock cuts sites (1, 2, 3, 4, 5, 6, 10, 14, 16, 17, and 18) have RMR values between 41 and 57 and are classified as fair. While, four locations (7, 11 12 13) have RMR values between 63 and 79 and are classified as good. One site which is 18 gave poor rock quality with RMR value of 37.

The RMR system was not applied in some sites such as 8, 9, 15, 20 and 21 because the degree of weathering is high (completely weathered), so the discontinuities are not well-defined and their properties could not be assigned. Also, the failure behaviour of these locations is most likely to be non-structurally controlled; discontinuities do not contribute to the occurrence of the failure, thus, the slope's instability could be affected by water and/or seismic forces (stress controlled failure).

The four rock mass classification systems are applied for only the structurally controlled sites. In this paper, planar failure mode has only been addressed for all these classification systems analyses. SMR (Romana, 1985) results for rock cuts indicate that all scores are below 50 and categorized from partially stable to unstable in conservative case (no limit range between the strike direction of slope face and joints). While, the SMR values will be decreased until less than 15 when the strikes difference between the slope face and the joint be around ±20, and the rock cuts will be categorized completely unstable (Table 1).

The Chinese SMR system is applied to the case studies without slope height factor as the heights of all sites are less than 50 m, and only the discontinuity factor (λ) has remained in the Chinese SMR equation. However, the results of this method show a significant increase in the SMR values than in Romana's system (Table 1). The reason for this increase is likely due to the low values of the discontinuity factor for most rock cuts with average value of 0.7. This means tight joints (high cohesion), which leads to increased SMR values and thus an increase in the degree of the stability condition.

The results of the continuous SMR (Table 1) indicated that the range of SMR values are between 29 to 46, and it can be observed that the results of this method are in a reasonable range, where there are no abnormal values as found in the discrete SMR by Romana, where some values are below 10 as in sites 1, 4, 10.1 and 22. Therefore, the continuous functions for the corrections F1, F2 and F3 gave some kind of reality to SMR scores.

The graphical SMR method results (Table 1) indicate that there are no differences between this system and Romana's system results. The reason for these similarities in the results probably due to the concept used in the graphical system was the same of the original SMR (Romana, 1985), which is the discreet rating for the correction factors of F1, F2, and F3, but the difference was in the method of application by using the stereo plots to determine these correction factors.

There are some difficulties in application of the graphical method especially in adjustment factor (F3), when the slope face angle is equal to or more than 80°, which makes the application of graphical method impossible, such as in sites 6, 7.2, and 10.2.

5. CONCLUSION

Four empirical methods, SMR (Romana, 1985), Chinese SMR (Chen, 1995), Continuous SMR (Tomas, 2007) and Graphical SMR (Tomas, 2012) are applied to twenty-two sites of rock cuts located in a rugged area along mountainous roads in the southwestern part of Kingdom of Saudi Arabia.

The main purpose of this study is to validate these classification methods, and compare their results for assessment the stability conditions of the rock cuts.

All these methods take into account condition of the rock mass presented by RMR system, and the relationship between the dip and the direction of slope face and joints which presented by the correction factors of F1, F2, and F3, as well as the effect of the method of excavation (F4).

The results of discrete SMR (Romana, 1985) give varying scores for SMR and not in tight range where in some locations the values are underestimated.

Chinese SMR adds two factors to the original SMR formula, slope height factor ad discontinuity factor, but in this study the factor for slope height has been eliminated, as the slope height for all case studies is below 80m. Although, the discontinuity factor has enhanced the SMR values, but the factor of slope height makes this method not applicable in a correct manner in rock cuts below 80m, as the height will be ineffective.

The continuous SMR system results showed no large difference among the scores unlike the discrete SMR by Romana because new continuous functions have been proposed in this method for adjustment factors F1, F2, F3 calculations rather than the discrete function in Romana's system.

The graphical SMR system has also been used in this analysis, and it has been observed that the results of this method have almost the same results of Romana's system as both of them using the discrete method to determine the correction factors of the relation between the slope face and the joints.

In conclusion, the continuous SMR that is proposed by Tomas (2007) is closest to the reality from the other methods. Also if the continuous RMR (Sen and Sadagah, 2002) used rather than the discrete RMR (Bieniawski, 1989), this may lead to enhance

Table 1: Results of the four empirical methods in case of plane failure mode for structural failure sites.

Site No.		Slope face	Joint	**SMR** (1985)	**CSMR** (1995)	**CoSMR** (2007)	**GSMR** (2012)	Field observations
1		60/040	51/040	7	22	46	7	MW, slope height 18m
2		69/014	46/341	31	34	29	31	MW, slope height 19m
3		77/055	40/095	35	38	32	35	MW, slope height 15m
4		60/269	55/283	9	12	33	9	MW, slope height 8m
5		78/020	No (P)	-	-	-	-	MW, slope height 19m
6		80/026	No (P)	-	-	-	N/A	MW, slope height 11m
7	1	70/190	62/195	13	26	45	13	SW, slope height 18m
			58/244	47	50	46	47	
	2	80/010	70/050	48	51	45	N/A	SW, slope height 31m
8		Soil-rock slope (completely weathered)						Slope height 13m

Table 1: Continued.

Site No.		Slope face	Joint	**SMR** (1985)	**CSMR** (1995)	**CoSMR** (2007)	**GSMR** (2012)	Field observations
9		Soil-rock slope (completely weathered)						Slope height 13m
10	1	70/285	40/275	4	4	36	11	MW, slope height 30m
	2	88/285	40/275	38	4	36	N/A	
			77/239	38	38	36	N/A	
11		76/320	No (P)	-	-	-	-	MW, slope height 10m
12		70/250	No (P)	-	-	-	-	MW, slope height 8m
13	1	67/030	66/015	20	30	45	20	MW, slope height 18m
			34/080	47	50	45	48	
	2	74/023	66/015	12	25	46	12	
			34/080	48	51	44	48	
14		66/095	44/059	38	41	22	38	MW, slope height 22m
15		Soil-rock slope (completely weathered)						Slope height 26m
16		70/130	40/074	36	38	33	36	MW, slope height 33m
17		76/154	44/102	44	47	41	44	MW, slope height 23m
			64/186	43	46	42	43	
18	1	65/070	No (P)	-	-	-	-	HW, slope height 15m
	2	66/057	No (P)	-	-	-	-	
	3	74/008	70/008	41	44	38	41	
19		74/190	55/209	3	16	34	3	HW, slope height 36m
			60/225	36	39	34	36	
20		Soil-rock slope (completely weathered)						Slope height 11m
21		Soil-rock slope (completely weathered)						Slope height 28m
22		65/140	50/154	8	20	39	8	MW, slope height 29m

(P) Planar failure. (SW) Slightly weathered. (MW) Moderately weathered. (HW) Highly weathered.

the SMR values and unique scores for SMR will be assigned to the rock cuts (Tomás et al. 2007).

These empirical methods are suitable only with structurally controlled slopes, and for non-structurally controlled slopes (highly weathered slopes) will be difficult to apply as the structures features are not well-defined, and the stress control factors will be unknown (i.e. water pressure and seismic force).

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