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Geological strength index$_{\text{-slope}}$: an adaptation of the geological strength index system for use in the rock slope stability assessment

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Abstract

The Geological Strength Index (GSI) system is the basis of parameters used in the Hoek-Brown failure criterion for rock mass strength estimation. The author tested this system and here suggests a modified GSI called Geological Strength Index-$_{\text{slope}}$ (GSI$_{slope}$). The modified system combines two different existing approaches: the GSI system and Slope Mass Rating (SMR). The purpose of GSI$_{slope}$ is to allow engineering geologists to quickly evaluate the stability of natural and excavated slopes or open-pit mining in the field. GSI$_{slope}$ is computed by subtracting a constant value of 10 and the multiplication of adjustment factors for discontinuity orientation and slope (F1, F2, and F3, based on the parallelism of discontinuity and slope, discontinuity dip angle, and the difference between the inclination angle of discontinuity and slope) from GSI, and adding field groundwater rating to it. Modified curves are also proposed in this work to determine the accurate ratings of the adjustment factors. The results of this work are compared to the values obtained from equations of continuous-SMR and SMR-value itself for both the adjustment factors and GSI$_{slope}$ values. The comparison showed that the proposed curves and GSI$_{slope}$ equation are valid and easy to use for estimating the adjustment factors' ratings and GSI$_{slope}$ value.

KEYWORDS: slope stability; geomechanical system; geological strength index; rock mass rating; slope mass rating; geological strength index-$_{\text{slope}}$.

INTRODUCTION

This study introduces a new system, the Geological Strength Index-$_{\text{slope}}$ (GSI$_{slope}$), which can be used for rapidly evaluating rock slope stability in the field. It offers simple ideas about stability conditions and instability modes.

GSI$_{slope}$ system combines two different existing approaches: GSI and Slope Mass Rating (SMR) systems. The GSI system is applied as a tool to determine the rock mass strength (Hoek and Brown 1997, 2019, Hoek and Diederichs 2006, Marinos and Carter 2018), and the SMR is applied to determine the stability condition (Romana 1985).

The GSI application for slopes has not been currently probable. The GSI$_{slope}$ system uses adjustment factors of Romana's (1985, 1993) SMR. Field guidelines permit the rapid use of this system for the rock slopes.

The GSI was innovated by Hoek (1994), Hoek *et al.* (1995), and Hoek and Brown (1997) to gain victory over the defects in Bieniawski's (1976, 1989) rock mass rating (RMR) for very poor-quality rock masses. This system supplies an estimate for the reduction of the rock mass strength for various geological conditions, which can be done in the field (Hamasur 2009).

The GSI is one of the excellent rock mass classification systems that is employed to assess very weak and heavily jointed rock mass. In addition to generalized Hoek-Brown constants, modulus of deformation, and properties of strength for an approximate style of tunnels and caverns, it can be applied by other ways of dealing and associated with rock mass properties. The difference of this system from other geotechnical systems is as follows: it uses field observation, represented by the structure of rock mass and discontinuity surface conditions, throughout the assessing method of rock mass and is strongly considered a practical tool for estimating the rock mass strength properties needed for the pre-stability task of engineering projects (Hussian *et al.* 2020).

After the growth of the GSI system, various researchers throughout the world have achieved research on multiple sides of the GSI system to adapt the weakest, jointed, and heterogeneous rock mass for the design of engineering projects (Marinos *et al.* 2005, Hoek et al. 2013, Vásárhelyi and Kovács 2017, Hoek and Brown 2019). The basic GSI chart, for use with jointed and very weak rocks, is shown in Fig. 1.

GSI$_{SLOPE}$ IDEA, TABLES, AND CURVES

The proposed GSI$_{slope}$ is computed by subtracting a constant value of 10 and the product calculation of adjustment factors for orientation of discontinuities and slope of the SMR

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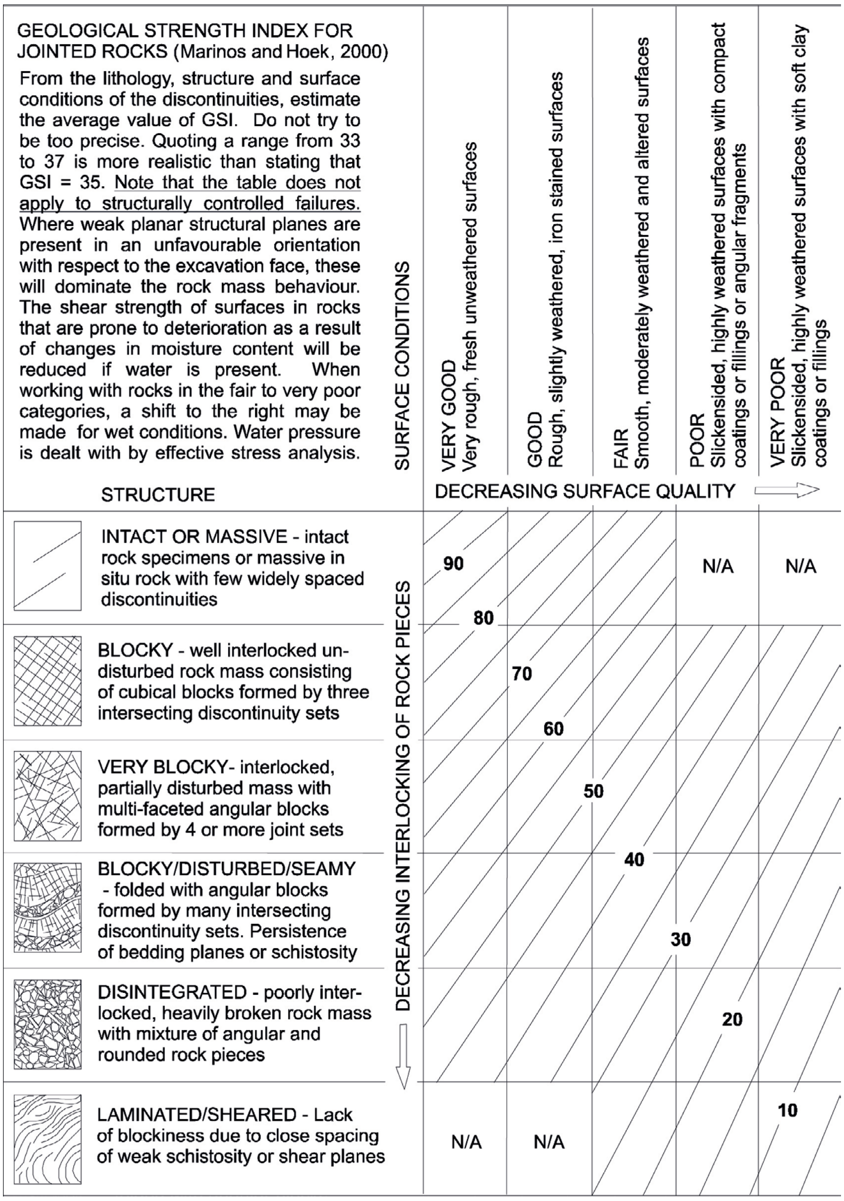
(F1, F2, and F3, based on the parallelism of discontinuity and slope, discontinuity dip angle, and the difference between the inclination angle of discontinuity and slope) from GSI, and adding an actual field groundwater rating (WR) to it, as follows (Eq. 1):

$$GSI_{slope} = GSI - 10 + WR + (F1.\ F2.\ F3) \quad (1)$$

The GSI = RMR_{1976} (Hoek *et al.* 1995, Hoek and Brown 1997), and the GSI value is equal to the rating for the first four parameters of RMR_{1976} (unconfined compressive strength of intact rock, rock quality designation [RQD], discontinuity spacing, and discontinuity condition); also, the rock mass should be assumed to be completely dry, and a rating of 10 is assigned to the groundwater value (Hoek *et al.* 1995, Hoek and Brown 1997); so, to determine the actual field WR, the value of 10 can be subtracted from the GSI value, and determine the groundwater condition in the field, the rating can be estimated from Bieniawski's RMR table (Table 1) (Bienawski, 1976).

The GSI system assumes a very favorable discontinuity orientation, its rating is set to zero, and the RMR system of Bienawski (1976; 1989) does not give a precise rating of the discontinuity orientation condition because it depends on the personal diligence and judgment. The most important geotechnical system that offers a precise rating for the discontinuity



Source: Marinos and Hoek (2000).
Figure 1. Basic GSI chart.

Table 1. Groundwater rating.

Groundwater	General conditions	Completely dry	Moist only	Water under moderate pressure	Severe water problems
	Rating	10	7	4	0

Source: Bienawski (1976).

orientation condition in the rock slopes is the SMR of Romana (1985, 1993) and Tomás *et al.* (2007); so, in this study, the last one is preferred.

The adjustment rating of the discontinuity orientation is the product of the same three factors proposed by Romana (1985) for the SMR system, and is given as follows:

(i) F1 is the rating of the difference in dip direction between discontinuity and slope face or between the plunge direction of two discontinuities and slope face;

(ii) F2 is the rating of the dip angle of discontinuity or plunge angle of the intersection line of two discontinuities;

(iii) F3 is the rating of the difference in dip angle between discontinuity and slope dip angles or between the plunge angle of the intersection line of two discontinuities and slope angle (Hamasur *et al.* 2020).

Instead of the tables of Romana (1985) and Anbalagan *et al.* (1992) and the equations of Tomás *et al.* (2007), the rating of these three adjustment factors (F1, F2, and F3) can be obtained from the curves shown in Figs. 2–5. The researcher of this article benefited from the equations of Tomás *et al.* (2007) in drawing these curves.

COMPARISON BETWEEN CONTINUOUS-SMR AND GSI_{SLOPE}

To prove the validity of GSI_{slope} system, the data of rock mass structure and surface conditions of discontinuities were used from Verma *et al.* (2011) and Hamasur and Qadir (2020) in order to determine the rock mass GSI value for all the 4 slope locations and all the 10 slope stations, as shown in Fig. 6.

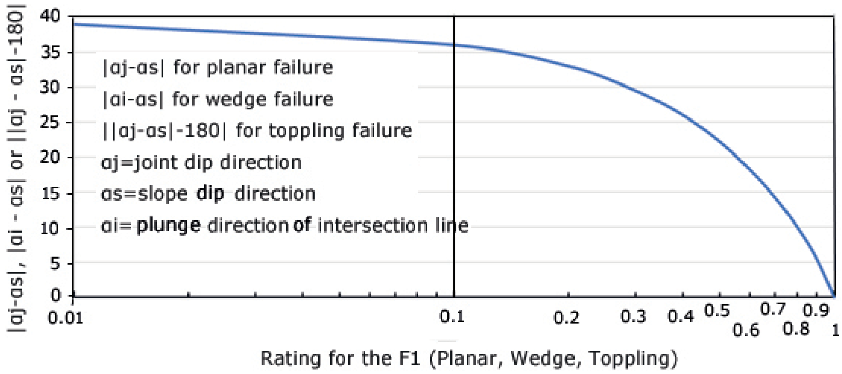


Figure 2. Variation of rating for the adjustment factor no. 1 (F1).

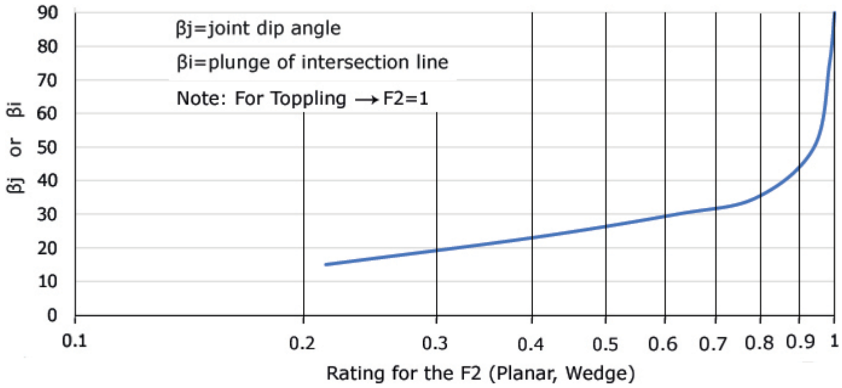


Figure 3. Variation of rating for the adjustment factor no. 2 (F2).

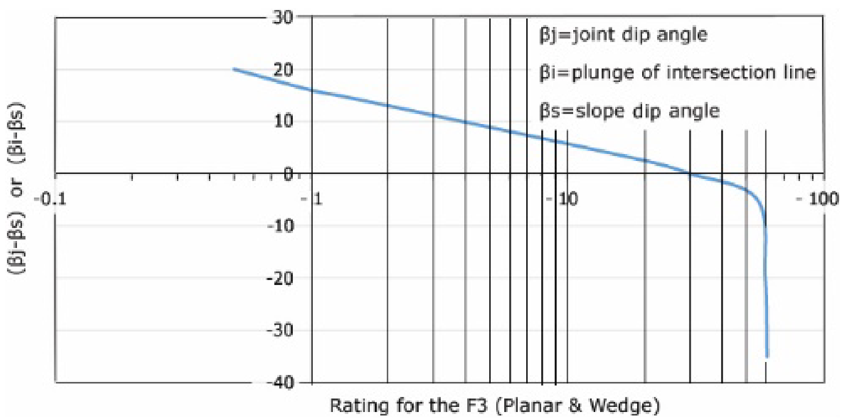


Figure 4. Variation of rating for the adjustment factor no. 3 (F3) (Planar & Wedge failure).

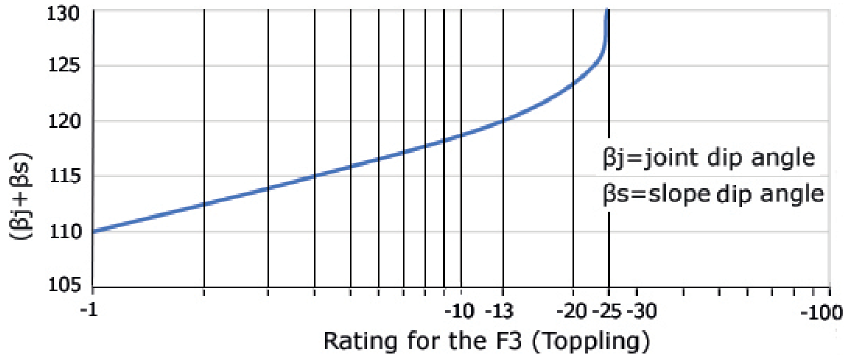


Figure 5. Variation of rating for the adjustment factor no. 3 (F3) (Toppling failure).

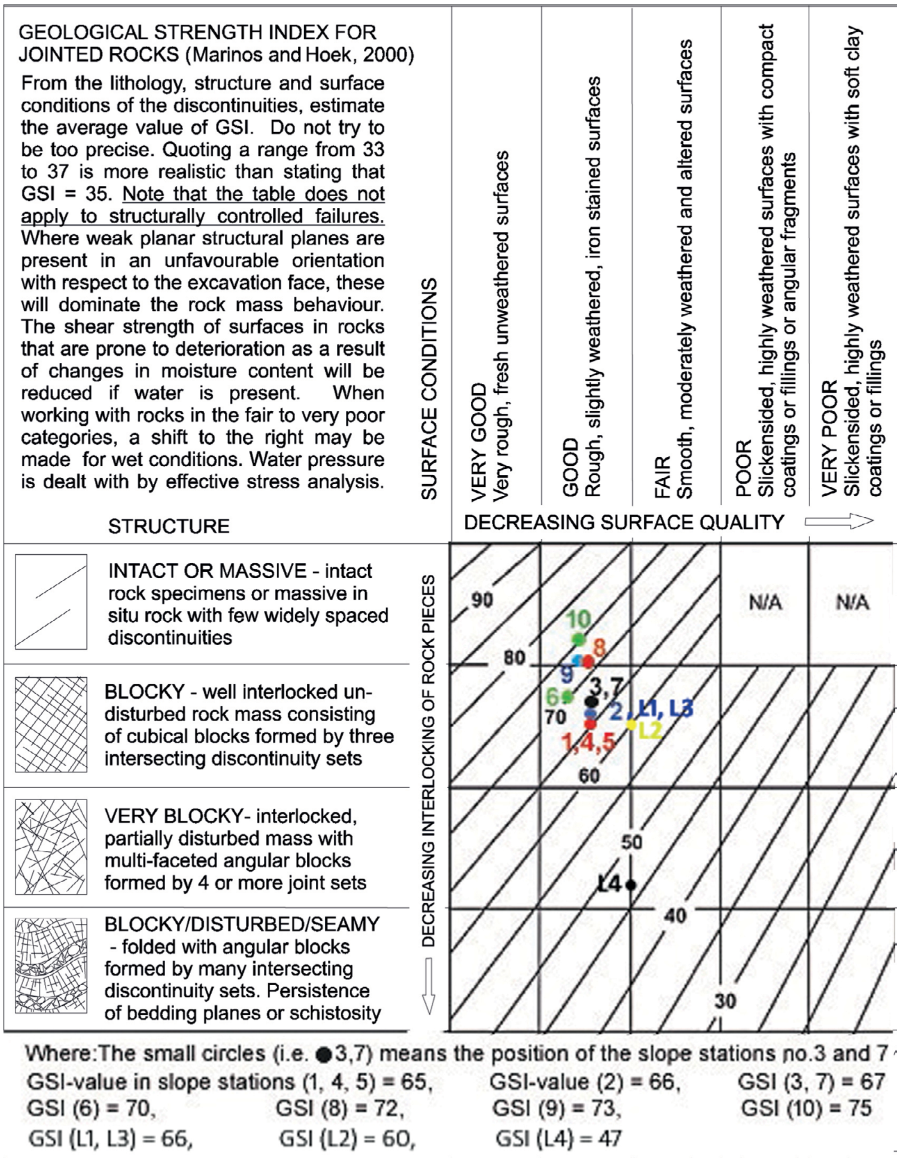


Figure 6. Value of the GSI in the 10 rock slope stations (circles with number) of Hamasur and Qadir (2020), and in the 4 slope locations (circles with letter and number) of Verma *et al.* (2011).

Verma *et al.* (2011) assigned the groundwater condition as completely dry for slope locations no. 1, 2, and 3, with the rating value of 10, and moist (damp) for slope location no. 4, with the rating value of 7. Also, Hamasur and Qadir (2020) determined the rating of the actual field groundwater to be equal to 7; this value is the average of dry condition (May-October) that has a value of 10 in RMR_{1976} and water under moderate pressure (November-April) that has a value of 4 in RMR_{1976}.

Adjustment factors (F1, F2, and F3) were determined from the attitude of discontinuities and slope by modified curves of this study; then, the product calculation of these three factors was determined. The GSI_{slope} value for 19 data sets was calculated in the mentioned 10 slope stations, using Eq. 1, and the results are shown in Table 2.

The adjustment factors F1, F2, and F3 calculated from the curves of this study represent similar results to those obtained from the continuous-SMR equations, despite the presence of ± 3° changes in the (F1. F2. F3) product calculation by the two methods in some cases. In addition, the calculated GSI_{slope} value from this study has approximately similar results compared to the continuous-SMR value, despite the presence of ± 3° changes by the two methods in some cases (Tables 2 and 3). However, these small changes do not affect the stability classes and conditions because the GSI_{slope} value has ranges of 20 scores between classes and conditions, as shown in Table 4.

STABILITY CLASSES AND CONDITIONS

After calculating the GSI_{slope} value, the stability classes and conditions of the rock slope can be determined from Table 4, which is modified from Romana's (1985) description table of slope mass rating classes to adapt to GSI_{slope}.

Table 2. Comparison between continuous-SMR and GSI_{slope} (data of continuous-SMR are from Hamasur and Qadir 2020).

Slope	Failure	Continuous-SMR				GSI_{slope} (from this study)			
Station	Type	$RMR_{b\,(1989)}$	F1.F2.F3	SMR	GSI	GSI-10	F1.F2.F3	WR	GSI_{slope}
1	FT	63	-21.28	41	65	55	-20.00	7	42
	DT	63	-9.65	53	65	55	-9.09	7	53
2	WS	65	-23.62	41	66	56	-24.51	7	38
	FT	65	-20.27	44	66	56	-19.20	7	44
3	WS	64	-45.94	18	67	57	-44.23	7	19
	FT	64	-21.11	42	67	57	-19.84	7	44
4	WS	62	-29.44	32	65	55	-30.26	7	32
	FT	62	-23.56	38	65	55	-22.50	7	39
5	PS	63	-44.17	19	65	55	-42.35	7	20
	WS	63	-52.68	10	65	55	-50.63	7	11
	DT	63	-0.54	62	65	55	-0.50	7	61
6	WS	70	-23.46	46	71	61	-24.60	7	43
	FT	70	-17.72	52	71	61	-17.25	7	51
7	PS	67	-32.64	34	67	57	-32.49	7	32
	FT	67	-22.04	44	67	57	-22.00	7	42
8	WS	69	-45.12	23	72	62	-43.89	7	25
	FT	69	-19.85	49	72	62	-18.84	7	50
9	PS	73	-40.50	32	73	63	-40.19	7	30
10	FT	71	-17.65	53	75	65	-16.10	7	56

PS: Planar sliding; WS: Wedge sliding; FT: Flexural toppling; DT: Direct toppling; SMR: Slope Mass Rating; F1, F2, and F3 are adjustment factors of continuous-SMR; GSI: Geological Strength Index; WR: water rating; GSI_{slope}: GSI-10+(F1.F2.F3)+GW.

Table 3. Comparison between continuous-SMR and GSI_{slope} (data of continuous-SMR are from Verma *et al.* 2011).

Slope Station	Failure Type	Continuous-SMR				GSI_{slope} (from this study)			
		$RMR_{b\,(1989)}$	F1.F2.F3	SMR	GSI	GSI-10	F1.F2.F3	WR	GSI_{slope}
Location 1	PS	65	-19.99	45.01	66	56	-22.03	10	43.97
Location 2	PS	60	-33.15	26.85	60	50	-36.00	10	24.00
Location 3	FT	65	-15.39	49.61	66	56	-18.75	10	47.25
Location 4	FT	50	-24.37	25.63	47	37	-20.50	7	23.50

PS: Planar sliding; FT: Flexural toppling; SMR: Slope Mass Rating; F1, F2, and F3 are adjustment factors of continuous-SMR; GSI: Geological Strength Index (the GSI value obtained from projection of Verma *et al.* (2011) information on GSI-Chart); WR: water rating; GSI_{slope}: GSI-10+(F1.F2.F3)+GW.

Table 4. Description of GSI_{slope} stability classes and conditions.

GSI_{slope} value	100←81	80←61	60←41	40←21	< 21
Stability class	I	II	III	IV	V
Stability condition	Completely stable	Stable	Partially stable	Unstable	Completely unstable

Source: modified from Romana (1985).

CONCLUSION

Rock mass engineering classification systems are a global system for those who use them. Engineering classification systems are widely utilized to predict the possible failures in the rock slopes, such as SMR, continuous-SMR, and Q-slope; these systems are among the most important classifications for slope stability assessment. Nevertheless, the GSI system does not use it to assess the rock slope's stability conditions.

In this study, the author tested and suggested a modified GSI called GSI_{slope}. The purpose of GSI_{slope} is to allow engineering geologists to quickly assess the stability of natural and excavated rock slopes or open-pit mining in the field. In addition, modified curves for evaluating adjustment factors have been proposed. The results from this work are compared to the values obtained from equations of continuous-SMR and SMR-value itself for both the adjustment factors and GSI_{slope} values. The comparison showed that the proposed curves and GSI_{slope} equation are valid and easy to use in the field for estimating the adjustment factors' ratings and GSI_{slope} value.

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