Journal of Geological Resource and Engineering 10 (2022) 1-13
doi:10.17265/2328-2193/2022.01.001

The Effectiveness of Blastability Quality System on Rock Slopes: A Case Study in a Landslide Restoration

Maria Chatziangelou[1] and Costas Anagnostopoulos[2]

1. Aristotle University of Thessaloniki, Thessaloniki 54124, Greece

2. International Hellenic University, Sindos 57400, Thessaloniki, Greece

Abstract: The significance of this paper is the evaluation of the use of BQS (blastability quality system) on rock slopes in practice A landslide, which took place in Northern Greece, in a tectonic active fault damage zone of gneiss and sandstone, and is used for our investigation. The results of the BQS description are combined with the results of the SMR (slope mass rating) Classification. The final results of the two classification methods are similar. It is significant that the both estimates are really close. So, the BQS can effectively be used as a combinational classification system and results in the appropriate support measure. The decision about the installation of the support measures mainly depends on the worst rock mass. Considering the presence of the active fault and the rock mass quality, the appropriate restoration can be a flexible system with gabions and benches, which follow the geometry of the potential critical sliding cycle. The above flexible support system can follow the fault movement during future earthquakes and absorb the energy and deformation. The cracked small wedges can be prevented from sliding by wire mess. Also, a drainage system and toe ditch need to drive the water of the rainfall out of the slope.

Key words: Landslide, rock mass, classification, support, slope stability.

1. Introduction

In situ geometrical data and the qualified rock mass characteristics are used for understanding the mechanism of the landslide. The qualified characteristics are also used to classify the rock mass according to BQS (blastability quality system) [1] and to SMR (slope mass rating) classification system [2]. The results are combined and the effectiveness of BQS is considered.

The correction factors which are used by RMR (rock mass rating) system have wide range and they can be described with different ways [3]. Although RMR is widely used in tunnelling [4], it has not been designed to be used in slopes [5]. The idea of SMR classification had been devised and relied on RMR system in order that the classification can be applied on slopes. On the other hand, the BQS system connects blastability [6] and rock mass quality. It can be easily used on rock masses so as the quality of rock mass and the BI (blastability index) can be quickly calculated [7]. BQS has been used to investigate the effect of the characteristics of rock mass quality on the result of blasting. Blastability is the property, which makes certain the ease of rock mass exploration under specific design of blasting, the quality and quantity of explosives and the constraints which are related to law and depend on the site peculiarities [8]. The rock mass quality, which is described by the widely used rock mass classification systems GSI (Geological Strength Index), and RMR, and the blast ability index are combined in the BQS [9]. The rock mass characterization system GSI refers to rock mechanics and combines the data which are related with the properties of the rock mass and are used for the design of the tunnels, foundations and slopes [10]. The GSI and the RMR are also estimated using BQS. The GSI is proposed for use in the Hoek and Brown failure criterion as it is able to provide effective solution to designing problems [11]. Hoek-Brown failure

Corresponding author: Maria Chatziangelou, Ph.D., research field: engineering geology.

criterion is empirical, which imports the rock strength with the major and minor principal stresses [12, 13].

2. Material and Methods

A movement of a slope's gravity center activates a landslide which rapidly displaces the adjacent geological formations. The movement is usually triggered by storms which produce heavy rains that last longer than several hours or days [14]. The rainfall rapidly infiltrates into the slope, so the water causes the saturation of the rock mass or the soil and raises the pressures in pores which are filled with it [15].

In situ data are used for understanding the mechanism of the landslide and to classify the quality of the rock mass, so as to propose the suitable support measures [16]. The geometrical data of the slope and the orientation of the tectonic data are used to stereo net for the estimation of the landslide kinematics. The qualified characteristics are also used to classify the rock mass according to BQS and to SMR. The results are combined and the effectiveness of BQS is considered.

The idea of SMR classification had been devised and relied on RMR system in order that the classification can be applied on slopes. So, the stability of the rock slope can be estimated with SMR. An SMR's advantage is the detailed quantitative definition of the correction factors [17]; the intact rock's strength, the RQD (rock quality destination), the joints spacing and condition, and the conditions of the ground water are also described on SMR use. The RQD measures the percentage of "good" rock within a borehole [18]. It has been shown that there is also a correlation between RQD and the Jv (volumetric joint count) [19]. For the use of SMR, the result is adjusted using four factors which account for the relative joints orientation in connection with the dip direction of the slope.

The BQS connects blastability and rock mass quality. It can be easily used on rock masses so that the quality of rock mass in addition the BI can be quickly calculated. BQS has been used to investigate the effect of the characteristics of rock mass quality on the result of blasting. Blastability is the property, which makes certain the ease of rock mass exploration under specific design of blasting, the quality and quantity of explosives and the constraints which are related to law and depend on the site peculiarities. The widely used classification items RMR and GSI are combined by BQS and information about the quality of rock mass and blastability is exported [9]; The rock mass characterization system GSI, which refers to rock mechanics, combines the data which are related with the properties of the rock mass and are used for the design of the tunnels, foundations and slopes [20]. The GSI was proposed for use in the Hoek and Brown failure criterion and it is further elaborated on very weak, sheared [21] and heterogeneous [22] rock masses. It is able to provide effective solution to designing problems. Hoek-Brown failure criterion is empirical, which imports the rock strength with the major and minor principal stresses [13, 23]. The strength estimations agree with the values which are determined from laboratory triaxial tests of intact rock [24, 25].

3. *In Situ* Data

The Atrium Hotel is placed in Northern Greece in a tectonic fault damage zone (Fig. 1).

The landslide took place in the eastern part of the hotel area after intense and continuous raining in July 2018 (Fig. 2). The rainfall duration was about 48 h. According to Kluger et al. [26], rainfall duration of 25 h is a critical threshold for landsliding. The rainfall increases the weight of the slope materials and calibrates a new effective stress which decreases the slope's effective stress. The intensity and the duration of the rainfall also increase the level of the effective stress. That is, the rainwater accelerated the sliding of wedges which activated the rotational slide of the weathered rock. At the left side of the landslide the tectonic contact between gneiss and sandstone, a fault

Fig. 1 Landslide location.

26/54 F (Fig. 3), with filling material of clay 40 cm thick, is visible. The upper formation, above the fault plane, is a tectonic mélange (Fig. 4). The mélange contains blocks of gneiss and weathered sandstone. There is a long discontinuity with mean surface of 270/32 J into the mélange. The formation, which is subjected to the fault, is weathered gneiss. The bedding is 279/10 S and the mean surface of the discontinuity system is 103/43 J.

4. Rock Mass Classifications

4.1 Rock Mass Quality Classification according to BQS

The different geological formations are classified according to the density of the rock mass discontinuity systems. As it usually occurs, the fault damage zone is jointed, weathered and the quality is worse than the global rock mass. For this reason, the fault damage zone is separately classified. So, there are four rock mass areas which have different qualities: (1) mélange (Fig. 4), (2) fault damage zone into mélange, (3) gneiss (Fig. 5), (4) fault damage zone into gneiss.

According to the BQS (see Appendix), the GSI and RMR can be directly estimated. The GSI is estimated; (i) for mélange, between 40 and 50; (ii) for gneiss, between 38 and 50; and (iii) for the different formations as a unit, taking into account fault damage zone, between 17 and 25.

Fig. 2 A part of the landslide.

Fig. 3 The clayey filling material of the fault 26/54 F at the left side of the slope.

Fig. 4 Tectonic mélange.

Fig. 5 Geological formation at the landslide area.

According to BQS, the RMR for gneiss formation and for fault damage zone is estimated 41-60. So, the rock mass subjected to the fault is characterized as medium (class III). According to BQS, the RMR of mélange is 61-80 and the quality of the rock mass is characterized as good (class II). Also, the quality of the blocks of gneiss in the mélange is very good (class I, RMR = 81-100) [27].

According to the above data, the quality of the rock mass is divided into the upper strata of good quality and the lower strata of medium quality. The decision about the installation of the support measures mainly depends on the lower strata where the rock mass quality is the worst. So, if the lower stratum is supported effectively, it assures the main percent of stability.

4.2 SMR Classification System

The geotechnical characteristics which are used for SMR classification are:

- Strength of rock mass: The rock mass relaxation is due to the weathered sandstone material in the overlying mélange formation. The weathered sandstone material degrades rock mass geotechnical properties. So, the weathered sandstone is shattered easily under moderate geological hammer blows. Therefore, the strength of rock mass is between 25 and 50 MPa [28].
- RQD: The Jv is calculated 84.25 and 77.57 (Fig. 6). That means: RQD = 0. Furthermore, the fault damage zone is also appeared after the removal of the vegetal.

Fig. 6 The spacing of discontinuities in gneiss.

The presence of the fault damage zone and the mélange minimize the RQD [29].

- Spacing of discontinuities: The orientation of the densest discontinuity system is 103/43 and the spacing of discontinuities is 15 cm.
- Discontinuities persistence: The fault's persistence, which affects the slope stability, is more extensive than 20 m.
- Discontinuities separation and infilling: The discontinuities are generally closed. But the separation of fault is 45 cm and is filled with clay.
- Roughness of discontinuities: The discontinuities are generally rough, despite the slickenside along the two sides of the fault.
- Weathering: The sandstone of the melange is decomposed. It is even more weathered than the other geological formation. The other geological formation is classified as weathered.
- Ground water: There is no indication of groundwater. Taking into account that the landslide is located near to the coast, the sea level is 10 m below the foot. But as the landslide occurred after a heavy rainfall, the geological formation is wet. So, it is safer to consider a dripping flow rate [30].

Using SMR, the RMR is estimated 19 (see Appendix). According to *in situ* data, the dip direction of the slope is 120° and the potential sliding occurred along the joint of 103/43. So, F1, F2, F3 and F4 factors are estimated:

- F1 = 0.70
- F2 = 0.85
- F3 = -25
- F4 = +15 (natural slope)

Taking into account the above factors in addition to RMR:

$$SMR = RMR - (F1 \times F2 \times F3) + F4 =$$
$$19 - [0.70 \times 0.85 \times (-25)] + 15 = 48$$

From the above relation, the SMR is calculated 48 and the rock mass quality is characterized as medium (Class III).

4.3 Evaluation of BQS and SMR Results

The rock mass quality and the fault orientation affect the slope stability. The support needs to consist of uniform measures to stabilize the worst quality rock mass which is the fault damage zone in addition to the subjective gneiss. According to the BQS, the RMR of the worst quality of the rock mass is estimated between 41 and 60 and is characterized as medium. For the same reasons, taking into account the worst rock mass characteristics for SMR, the rock mass quality is medium and the SMR is calculated 48. It is obvious that the rock mass quality estimation according to SMR, which is calculated 48, is incorporated to RMR range 41-60, which is estimated according to BQS. The both classification systems result in the same (medium) rock mass quality. That means the both estimates are really close.

5. Friction Angle

The friction angle (φ) of the rock mass can be also estimated with two ways:

- Taking into account the GSI: The GSI of mélange is 40-50. Considering that material constant (m_i) is about 17 because of the matrix of sandstone, the friction angle is calculated by the Mohr-Coulomb failure criterion; φ = 53°. The GSI of gneiss is 38-50, m_i is 28, and φ is calculated 61°. Also, considering the rock mass as a whole, with the presence of the fault, the GSI is 17-25. m_i is 6 because of the gneiss separation around the fault zone. So, the φ is calculated 8° (Table 1).
- Taking into account the RMR: As the stability of the lower strata (medium quality) is critical for the slope safety, the cohesion (c) and φ are estimated for medium quality rock mass by Bieniawski [28].

So, c = 200-300 kPa and φ = 25°-35° (Table 1).

Table 1 shows the mechanical properties—rock mass strengths, cohesion, friction angle, modulus of deformation and the maximum stress [31] according

Table 1 Mechanical properties of the rock mass.

	Gneiss	Mélange	Whole rock mass
Hoek-Brown classification			
GSI	38-50	40-50	17-25
m_i	28	17	6
Intact uniaxial compressive strength (MPa)	175	75	0.6
Disturbance factor (mechanical excavation)	0.7	0.7	0.7
Hoek-Brown criterion			
Reduced value of m_i (m_b)	0.928	0.629	0.063
Constant s	0.0001	0.0002	$5.97e^{-5}$
Mohr-Coulomb Fit			
Cohesion c (MPa)	0.251	0.196	0.006
Friction angle φ (°)	61	53	8
Rock mass parameters			
Tensile strength (MPa)	0.024	-0.020	$-5.71e^{-5}$
Uniaxial compressive strength (MPa)	1.742	0.879	0.001
Global strength (MPa)	21.230	7.528	0.014
Modulus of deformation E (MPa)	3,257.72	3,165.51	75.33
Failure range			
Minor principal stress $\sigma_{3\,max}$ (MPa)	0.4055	0.3694	0.1497
Apparent weight (kN/m^3)	2.6	2.6	1.8

to GSI, Hoek-Brown failure criterion [24, 32], and Mohr-Coulomb [33].

6. Mechanism of Landslide

The slope plane, before the landslide, is plotted on stereo net with dip of 60° because 60° is the steepest inclination of slopes, which is used in road works (Fig. 7).

As it is shown on stereo net, there are potential wedges which are formed by the fault plane 26/54 F and the joint planes 103/43 J. Considering that the φ of the whole rock mass is less than 25°, the potential sliding occurred in the direction of 103/43 J [34, 35]. The φ of intact gneiss and melange are 61° and 53° respectively, and they are higher than the dips of the tectonic data. It is obvious that if the slope was not faulted, it would be stable. The presence of the faulted zone minimizes the mechanical properties and the quality of rock mass.

The rainwater easily penetrates the rock mass between the joints, increases the weight of the rock mass and erodes the minerals of gneiss turning the biotite, the amphiboles and feldspars into clay minerals, sustaining the laminated structure. Additionally, the cohesion of the rock mass is decreased, and the clayey filling material is swollen. Finally, the rock mass adopts soil properties and behaves like soil. The friction angle along the discontinuities surfaces was reduced, and the weight of the slope was increased with the presence of the water. So the rainwater accelerated the sliding of the wedges which activated the rotational slide of the weathered rock.

7. Support Measures

The successful installation of the support measures is very important for slope stability [36]. The measures must support a complex rock mass and not a homogeneous rock with repeated tectonic data. The anisotropic shear behavior of the rock mass [37] must be taken into account. Also, the fault damage zone which is filled with clay 40 cm thick is dangerous. The support measures cannot stop the movement of the fault, but they can follow the movement and absorb the energy and deformation. For this reason the support measures need to be flexible and not rigid. The gabions are appropriate to stabilize the slope.

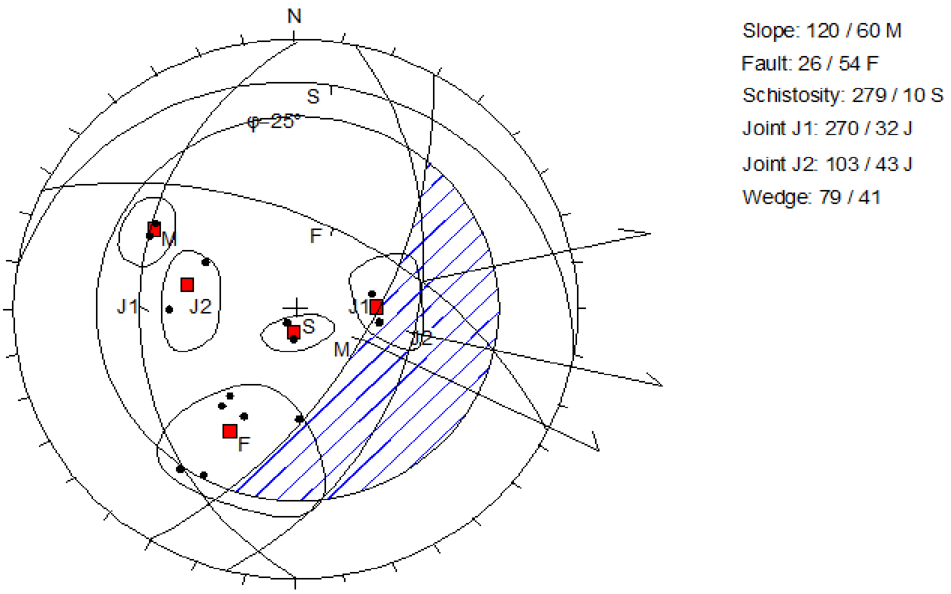

Fig. 7 Stereo net with tectonic data.

Taking into account the rock mass quality as it was estimated by the above classifications, the proposed support measures are:

- Benches which are constructed in different geometrical configurations, so that the slope can be balanced.
- Mass gravity gabion retaining walls which reinforced the benches in order to help the slope stability.
- Wire mess with systematic bolts for the small wedges sliding protection.
- Drainage system for driving the rainwater to a toe ditch in order to remove the water out of the slope [38, 39].

The best choice for supporting the slope depends on: (i) the planar sliding which took place at the beginning in order to activate the phenomenon, (ii) the rotational movement of the weathered rock mass, and (iii) the potential critical sliding cycle. The support measures must also protect the slope against the potential future failures.

8. Results

The area of the landslide is geologically located at the tectonic fault damage zone of gneiss and sandstone. The rainwater penetrated joints during the period of heavy rainfall and it caused the weathering of the geological formation, reducing the friction angle along the discontinuities surfaces, increasing the weight of the slope. So, the rainwater accelerated the sliding of the wedges, which are formed by the fault plane 26/54 F and the joint planes 103/43 J, in the direction of 103/43 J so, the rotational slide of the weathered rock was activated.

The fact that the rock mass is characterized as medium quality with both classification systems is an evidence that the BQS and the SMR are really close. So the BQS, which combines the majority of classical classification systems information, can effectively be used for understanding the rock mass quality and decide the appropriate support measures.

The proposed support depends on: (i) the planar sliding which took place at the beginning in order to activate the phenomenon, (ii) the rotational movement of the weathered rock mass, and (iii) the potential critical sliding cycle. The support measures must also protect the slope against the potential future failures. So, the proposed support measures are: (I) benches which are constructed in different geometrical configurations, (II) mass gravity gabion retaining walls, (III) wire mess with systematic bolts, (IV) drainage system and toe ditch.

9. Discussion

Rock mass classifications have helped make communication easier between engineers. They provide advisory information relating to numbers that can describe the rock mass with a universal way. RMR, SMR and GSI are different classifications, and they depend on the parameters which are controlled by variables that influence the final values. The same rock mass may be differently classified by the engineers as there are small differences between the variables and this can cause changes in the parameters.

In order to minimize the possibility of the different estimations of engineers, the BQS system connects the classical classification systems (RMR and GSI) so that all the factors can be taken into account. Furthermore, the BQS system gives additional information about the ability to decide the way in explosives' use to break rock for excavation. As RMR is designed to be used in tunneling and not in slopes and GSI is designed to be used in tunneling and slopes, there is a question how much the BQS is applicable in slopes. The significance of this paper is the evaluation of the use of BQS on rock slopes in practice.

The SMR classification, which is applied on slopes stability, depends on RMR classification system. The comparison between SMR results and BQS results proved that the BQS can effectively be used as a combinational classification system and result in the same appropriate support measure.

On the other hand, the paper describes the way of the BQS use. The more detailed description of the rock mass, the safer support design is resulted. The different geological formations are firstly classified as separated units. Moreover, they are classified as a uniform set so the influence of the contact between the formations can be shown.

10. Conclusions

In situ geometrical data and the qualified rock mass' characteristics are used for the classification according to BQS's and SMR's application.

The place of the application is located on the tectonic contact between gneiss and sandstone. The rock mass consists of tectonic mélange and weathered gneiss. Using the BQS,

- The GSI is estimated;

For mélange: 40-50.

For gneiss: 38-50.

The presence of the faults (tectonic contact) minimizes the GSI: 17-25.

- The RMR is estimated;

For mélange: 61-80 and the rock mass quality is characterized as good (class II).

For gneiss formation which includes fault damage zones: 41-60. So, the rock mass subjected to the fault of the tectonic contact is characterized as medium (class III).

For the blocks of gneiss which are placed in the mélange: 81-100 and the quality is characterized as very good (class I).

The purpose of the classification systems use is the determination of the suitable restoration. The support needs to consist of uniform measures to stabilize the worst quality rock mass. According to the BQS, as it is obvious from the above data, the RMR of the worst quality of the rock mass is estimated 41-60 and the rock mass characterized as medium. Talking into account the worst rock mass characteristics, the SMR is calculated 48, which means that rock mass is medium quality too. It is obvious that the rock mass quality estimation according to SMR, which is calculated 48, is incorporated to RMR range 41-60, which is estimated according to BQS. The both classification systems result in the same (medium) rock mass quality. That means the both estimates are really close.

The restoration must support a complex rock mass and not a homogeneous rock with repeated tectonic data. This is because the rainwater easily penetrates the rock mass between the joints, increases the weight of the rock mass and erodes the minerals of gneiss turning the biotite, the amphiboles and feldspars into clay minerals, sustaining the laminated structure. Moreover, the rock mass' cohesion is decreased, and the clayey filling material is swollen. Finally, the rock mass adopts soil properties and behaves like soil. The rainwater accelerates the sliding of the wedges which activate the rotational slide of the weathered rock.

Additionally, the presence of the faulted zone, which can activate sliding, in the future needs to be supported by flexible measures so they can follow the movement of the slope during a probable future earthquake and the same time every pressure on the foot of the slope needs to be exerted without rupturing, so that the slope can balance.

So, taking into account the rock mass quality as it was estimated by the above classifications, the proposed support measures are:

- Benches which are constructed in different geometrical configurations, so that the slope can be balanced.
- Mass gravity gabion retaining walls which reinforced the benches in order to help the slope stability.
- Wire mess with systematic bolts for the small wedges sliding protection.
- Drainage system for driving the rainwater to a toe ditch in order to remove the water out of the slope and minimize the pressure on the foot of the slope.

References

[1] Chatziangelou, M., and Christaras, B. 2017. "A New Development of BQS (Blastability Quality System) for Closely Spaced Formations." *Journal of Geological Resource and Engineering* 1: 24-37.

[2] Romana, N. 1985. "New Adjustment Ratings for Application of Bieniawski Classification to Slopes." In *Proceedings of the International Symposium of Rock Mechanics, Excavation, Mining & Civil Works*, Mexico City, Brazil, pp. 59-68.

[3] Pandelidis, L. 2009. "Rock Slope Stability Assessment through Rock Mass Classification Systems." *International Journal of Rock Mechanics and Mining Sciences* 46 (2): 315-25.

[4] Mohammadi, M. 2021. "Development of an Optimal Experimental Model for Predicting Rock Mass Rating Based on Tunneling Quality Index." *International Journal of Rock Mechanics and Mining Sciences* 140: 104602.

[5] Bieniawski, Z. T. 1979. "The Geomechanical Classification in Rock Engineering Applications." In *Proceedings of the 4th International Congress Rock Mechanics, Montreux*, Balkema, Rotterdam.

[6] Ajoy, G., and Akhilesh, J. 2012. *Blasting in Mining—New Trends*. New York: Taylor & Francis, CRC Press.

[7] Lilly, P. A. 1986. "An Empirical Method of Assessing Rock Mass Blastability." In *Proceedings of AusIMM/IEAust Large Open Pit Mining Conference*, Newman, pp. 89-92.

[8] Kaushik, D., and Phalguni, S. 2003. "Concept of Blastability—An Update." *The Indian Mining & Engineering Journal* 42 (8-9): 24-31.

[9] Christaras, B., and Chatziangelou, M. 2014. "Blastability Quality System (BQS) for Using It, in Bedrock Excavation." *Structural Engineering and Mechanics* 51 (5): 823-45.

[10] Marinos, V., Marinos, P., and Hoek, E. 2005. "The Geological Strength Index: Applications and Limitations." *Bulletin of Engineering Geology and the Environment* 64: 55-65.

[11] Marinos, P., and Hoek, E. 2000. "A Geologically Friendly Tool for Rock Mass Strength Estimation." In *Proceedings of International Conference on Geotechnical and Geological Engineering*, 1422-40.

[12] Sonmez, H., and Ulusay, R. 1999. "Modification to the Geological Strength Index (GSI) and Their Applicability to Stability of Slopes." *International Journal of Rock Mechanics and Mining Sciences* 36 (6): 743-60.

[13] Wu, F., and Wang, S. 2001. "Strength Theory of Homogeneous Jointed Rock Mass." *Geotechnique* 51 (9): 815-8.

[14] Ellen, S. D., Mark, R. K., Cannon, S. H., and Knifong. D. L. 1993. *Map of Debris-Flow Hazard in the Honolulu District of Oahu, Hawaii.* Geological Survey Open-File, Report.

[15] Min, K.-B., Rutqvist, J., and Elsworth, D. 2009. "Chemically and Mechanically Mediated Influences on the Transport and Mechanical Characteristics of Rock Fractures." *International Journal of Rock Mechanics and Mining Sciences* 46: 80-9.

[16] Bieniawski, Z. T. 1974. "Geomechanics Classification of Rock Masses and Its Application in Tunneling." In *Proceedings of 3rd International Congress of Rock Mechanics, ISRM*, Denver, pp. 27-32.

[17] Romana, M., Tomas, R., and Seron, J. B. 2015. "Slope Mass Rating (SMR) Geomechanics Classification: Thirty

Years Review." In *Proceedings of International Symposium on Rock Mechanics*, Quebec, Canada, p. 10.

[18] Deere D. U., and Deere, D. W. 1988. "The Rock Quality Designation (RQD) Index in Practice." In *Rock Classification Systems for Engineering Purposes*, edited by L. Kirkaldie, pp. 91-101.

[19] Palmstrom, A. 2005. "Measurements of and Correlations between Block Size and Rock Quality Designation (RQD)." *Tunnels and Underground Space Technology* 20: 362-77.

[20] Marinos, P., Marinos, V., and Hoek, E. 2007. "Geological Strength Index (GSI). A Characterization Tool for Assessing Engineering Properties for Rock Masses." In *Proceedings International Workshop on Rock Mass Classification for Underground Mining*, Mark, Pakalnis and Tuchman, pp. 87-94.

[21] Hoek, E., Marinos, P., and Benissi, M. 1998. "Applicability of the Geological Strength Index (GSI) Classification for Very Weak and Sheared Rock Masses. The Case of the Athens Schist Formation." *Bull. Eng. Geol. Env*. 547: 151-60.

[22] Marinos, P., and Hoek, E. 2001. "Estimating the Geotechnical Properties of Heterogeneous Rock Masses such as Flysch." *Bull. Eng. Geol. Env*. 60: 85-92.

[23] Ma, L. Li, Z., Wang, M., Wu, J., and Li, G. 2020. "Applicability of a New Modified Explicit Three-Dimensional Hoek-Brown Failure Criterion to Eight Rocks." *International Journal of Rock Mechanics and Mining Sciences* 133: 104311.

[24] Hoek, E., Carranza-Torres, C. T., and Corkum, B. 2002. "Hoek-Brown Failure Criterion." In *Proceedings of NARMS-TAC Conference*, Toronto, Cananda, pp. 267-73.

[25] Cai, M., Kaiser, P. K., Uno, H., Tasaka, Y., and Minami, M. 2004. "Estimation of Rock Mass Deformation Modulus and Strength of Jointed Hard Rock Masses Using the GSI System." *International Journal of Rock Mechanics and Mining Sciences* 41 (1): 449-66.

[26] Kluger, M., Moon, V., Jorat, E., and Kreiter, S. 2020. "Rainfall Threshold for Initiating Effective Stress Decrease and Failure in Weathered Tephra Slopes." *Landslides* 17 (2): 267-81. https://doi.org/10.1007/s10346-019-01289-2.

[27] Bieniawski, Z. T. 1993. "Classification of Rock Masses of Engineering. The RMR System and Future Trends." In *Rock Testing and Site Characterization*, pp. 553-73.

[28] Bieniawski, Z. T. 1989. *Engineering Rock Mass Classifications*. New York: Wiley-Interscience.

[29] Zhang, L. 2016. "Determination and Applications of Rock Quality Designation (RQD)." *Journal of Rock Mechanics and Geoechnical Engineering* 8: 389-97.

[30] Coppola, L. 2018. *Hydrogeological Instability in Cohesive Soils: Techniques for Prediction, Prevention and Control*. New York: Springer.

[31] Hoek, E., and Brown, E. T. 1997. "Practical Estimates of Rock Mass Strength." *International Journal of Rock Mechanics and Mining Sciences* 34 (8): 1165-86.

[32] Hoek, E., and Brown, E. T. 2018. "The Hoek-Brown Failure Criterion and GSI." *Journal of Rock Mechanics and Geotechnical Engineering* 11 (3): 445-63.

[33] Li, B., Jiang, Y., Mizokami, T., Ikusada, K., and Mitani, Y. 2014. "Anisotropic Shear Behavior of Closely Jointed Rock Masses." *International Journal of Rock Mechanics and Mining Sciences* 71: 258-71.

[34] Hocking, G. 1976. "A Method for Distinguishing between Single and Double Plane Sliding of Tetrahedral Wedges." *Int. Journal of Rock Mechanics & Mining Science* 13: 225-6.

[35] Markland, J. T. 1972. *A Useful Technique for Estimating the Stability of Rock Slopes when the Rigid Wedge Sliding Type of Failure Is Expected.* Imperial College Rock Mechanics Research Report.

[36] Bye, A. R., and Bell, F. G. 2001. "Stability Assessment and Slope Design at Sandsloop Open Pit, South Africa." *International Journal of Rock Mechanics and Mining Sciences* 38: 449-66.

[37] Li, B., Jiang, Y., Mizokami, T., Ikusada, K., and Mitani, Y. 2014. "Anisotropic Shear Behavior of Closely Jointed Rock Masses." *International Journal of Rock Mechanics and Mining Sciences* 71: 258-71.

[38] Bieniawski, Z. T. 1973. "Engineering Classification of Jointed Rock Masses." *Transactions of the South African Institution of Civil Engineers* 15: 355-44.

[39] Romana, M., Seron, J. B., and Montalar, E. 2003. "SMR Geomechanics Classification: Application, Experience and Validation." In *Technology Roadmap for Rock Mechanics*. South African: South African Institute of Mining and Metallurgy.

Appendix

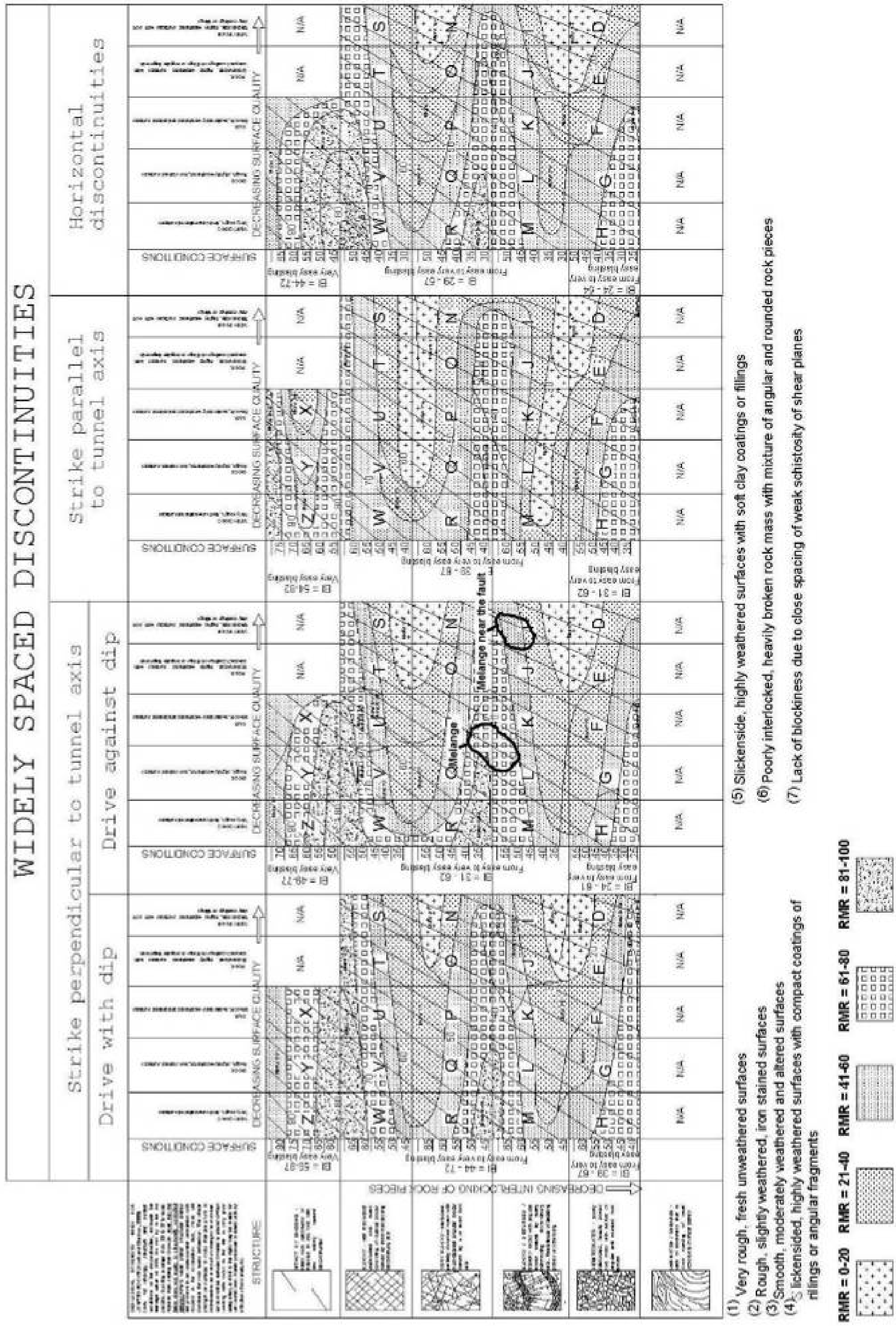

Fig. 1 Blastability quality system for mélange.

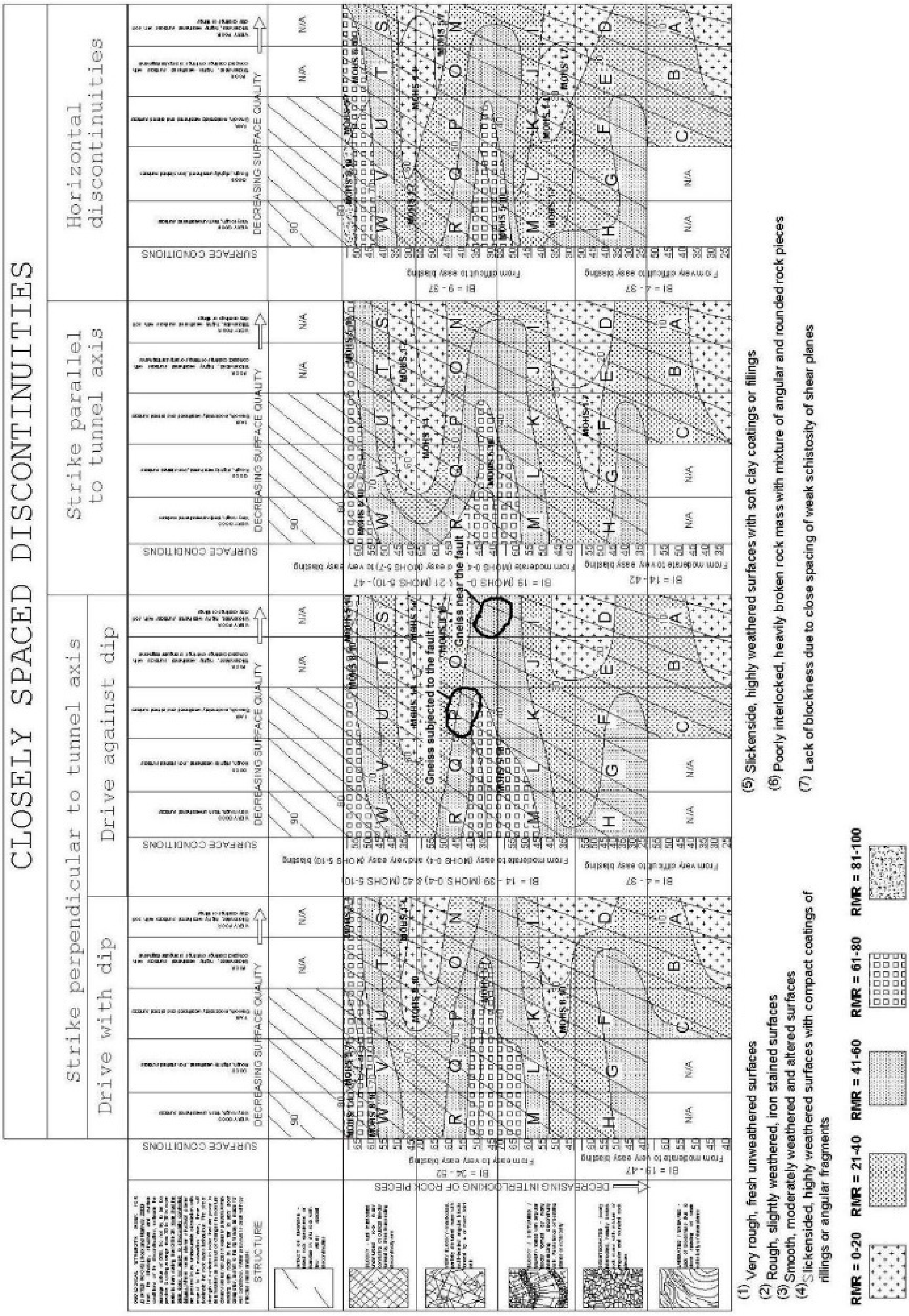

Fig. 2 Blastability quality system for gneiss.

STRENGTH OF INTACT ROCK MATERIAL (Mpa)			RATING	DRILL CORE QUALITY RQD			RATING
Uniaxial comp.strength (Mpa)	Point-load strength index			Very good	90-100%	☐	20
>250	>10	☐	15	Good	75-90%	☐	17
100-250	4-10	☐	12	Medium	50-75%	☐	13
50-100	2-4	☐	7	Poor	25-50%	☐	8
25-50	1-2	☒	4	Very poor	<25%	☒	3
5-25	<1	☐	2				
1-5		☐	1				
<1		☐	0	(RQD): Rock Quality Designation			

SPACING OF DISCONTINUITIES

		Joint set 1	Joint set 2	Joint set 3	Joint set 4	
Very wide spacing	> 2m	☒	☐	☒	☐	20
Wide spacing	0,8-2,0 m	☐	☐	☐	☒	15
Moderate spacing	200-800 mm	☐	☐	☐	☐	10
Close spacing	60-200 mm	☐	☒	☐	☐	8
Very close spacing	<60 mm	☐	☐	☐	☐	5

DISCONTINUITY CONDITIONS

PERSISTENCE		Joint set 1	Joint set 2	Joint set 3	Joint set 4	
Very low	<1 m	☐	☐	☐	☐	6
Low	1-3 m	☐	☒	☐	☐	4
Medium	3-10 m	☐	☐	☒	☐	2
High	10-20 m	☐	☐	☐	☒	1
Very high	>20 m	☒	☐	☐	☐	0
SEPERATION		Joint set 1	Joint set 2	Joint set 3	Joint set 4	
None		☐	☒	☒	☒	6
Closed	<0,1 mm	☐	☐	☐	☐	5
Medium	0,1-1,0 mm	☐	☐	☐	☐	4
Open	1-5 mm	☐	☐	☐	☐	1
Very open	>5 mm	☒	☐	☐	☐	0

ROUGHNESS

	Joint set 1	Joint set 2	Joint set 3	Joint set 4	
Very rough	☐	☒	☐	☐	6
Rough	☐	☐	☐	☐	5
Slightly rough	☐	☐	☒	☒	3
Smooth	☐	☐	☐	☐	1
Slickensided	☒	☐	☐	☐	0
INFILLING (GOUGE)	Joint set 1	Joint set 2	Joint set 3	Joint set 4	
None	☐	☒	☒	☒	6
<5 mm - Hard filling	☐	☐	☐	☐	4
>5 mm - Hard filling	☐	☐	☐	☐	2
<5 mm - Soft filling	☐	☐	☐	☐	2
>5 mm - Soft filling	☒	☐	☐	☐	0

WEATHERING

	Joint set 1	Joint set 2	Joint set 3	Joint set 4	
Unweathered	☐	☐	☐	☐	6
Slightly weathered	☐	☐	☐	☐	5
Moderately weathered	☐	☐	☒	☒	3
Highly weathered	☐	☒	☐	☐	1
Decomposed	☒	☐	☐	☐	0

GROUND WATER

INFLOW per 10m tunnel length (l/m)
or
JOINT WATER PRESS
or
GENERAL CONDITIONS

	Completely dry		Damp		Wet	Dripping
	☐ 15		☐ 10		☐ 7	☒ 4
Flow rate:	Low flow		Medium flow		High flow	
	☐ 0		☐ 0		☐ 0	

TEKTONIC DATA

Joint set 1:	24/54 F
Joint set 2:	279/10 S
Joint set 3:	270/32 J
Joint set 4:	103/43 J

Fig. 3 Rock mass classification SMR.