

Multi-Rock Mass Classification Systems for the Assessment of Excavation Method and Support Design of Spillway Tunnel, Sidan Dam, Bali, Indonesia

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Abstract. This paper presents the implementation of rock mass classification systems to determine the excavation method and the support design of the Spillway Tunnel, Sidan Dam, Bali, Indonesia. In order to mitigate the uncertainty associated with using single rock mass classification during designing tunnels, this study provides an evaluation by applying multiple rock mass classifications. Rock Mass Rating (RMR), Q-System, Geological Strength Index (GSI), Japan Society of Civil Engineering (JSCE), and Rock Mass Index (RMI) were among the rock mass classification systems used for comprehensive analysis. Rock mass parameters were determined based on engineering geological mapping and rock & soil core analysis. The rock mass quality of pyroclastic rock along the tunnel is generally poor to fair. Based on the GSI rating, digging and ripping excavation were recommended. The top heading with benching (1-3 m advance in top heading) was the proposed excavation method by RMR and JSCE. Each classification system advised the combination of reinforced shotcrete and rock bolt for the primary tunnel support with varying shotcrete thickness (30-400 mm), rock bolt length (2.6-6 m), and rock bolt spacing (1-2.5 m). However, field investigations during excavation and numerical stability analysis were recommended to eliminate risks and ensure safe construction.

1 Introduction

As part of its effort to achieve sustainable development goals, Indonesia has built numerous dams to preserve the quality and quantity of clean water. The Sidan Dam was built to resolve the province of Bali's water scarcity. Currently, construction of the dam is ongoing, with spillway tunnel construction scheduled to begin in 2022. This tunnel is in a horseshoe shape with approximately 11 m in diameter and 325 m in length. During the tunnel designing phase, the Rock Mass Rating (RMR) method was used to establish the rock mass classification at the research location. However, evaluation by utilizing other classifications is required to minimize risk, particularly when recognizing weak rocks.

The most widely used categorization methods are the RMR system, which Bieniawski presented in 1973, and the Q system, which Barton et al. initially identified in 1974. However, classification systems have been developed to solve engineering problems. Palmström introduced the RMI system in 1995, which is most applicable to massive, jointed, and crushed rock masses with identical properties of the joints in the various sets [1]. GSI system by Hoek and Marinos in 2000 could estimate the rock quality from a visual

examination [2]. Japan Society of Civil Engineers 2007 provided a classification system for Standard Specification for Mountain Tunneling [3].

Each system for classifying rock masses has limitations in terms of application [1]. On the other hand, one or more rock mass categorization methods may be used to develop an understanding of the composition and features of a rock mass to offer early estimates of support needs and estimations of the rock mass's strength and deformation properties [4]. Several tunnel constructions, including roads [5], railways [6], and dam tunnels [7], have already benefited from the application of multiple evaluation systems. Furthermore, this research could suggest the required type and the quantity of tunnel support.

1.1 Research Location & Geological Condition

Sidan Dam is located in the Province of Bali, Indonesia, on the boundary of three (three) regencies, namely Badung, Bangli, and Gianyar (Figure 1). It dams the Ayung River. This dam is expected to provide 1.75 cubic meters of clean water per second, a 0.65-megawatt micro-hydropower plant (PLTM), tourist sites, and environmental conservation.

Based on the Regional Geological Map of Bali, Nusa Tenggara [9], the lithology of the research

location includes the Volcanic Rocks of the Buyan-Bratan and Batur Group (Qpbb) of Early Holocene (quarter) age, which are composed of tuff and lahar flows. Meanwhile, according to the Geological Map of the Batur Caldera, Bali, Indonesia [10], the lithology of the research study consisted of the Penelokan Pyroclastic Fall Deposit Unit (Pnj) and the Blingkrang Freatomagmatic Deposit Unit (Bkp).



Fig. 1. Research Area [8]

2 Methodology

This experiment investigates the characteristics of engineering geology on and beneath the surface to establish the quality of the rock mass, as well as the tunnel excavation method and support design system. Geological mapping and sample analysis from the outcrops of the tunnel portal have been done to characterize the surface geological condition and rock properties. Additionally, discontinuity observations were also carried out based on excavation reports of the diversion tunnel that had been constructed (2020) parallel to the spillway tunnel locations with similar lithology and near distances.

The subsurface investigation is accomplished by observing the core's drilling report, description, and laboratory results. Borehole and tunnel design data were sourced from the Balai Wilayah Sungai Bali Penida. Spillway tunnel bore data from 3 drilled locations, BPS (2019), BHT-6 (2017), and BHT-7 (2017), were evaluated (Figure 2). The base map was generated and processed from the Digital Elevation Model of Badan Informasi Geospasial Indonesia.

The rock mass classification systems employed in this study include the Rock Mass Rating (RMR), the Q-System, the Geological Strength Index (GSI), the Japan Society of Civil Engineering (JSCE), and the Rock Mass Index (RMi).

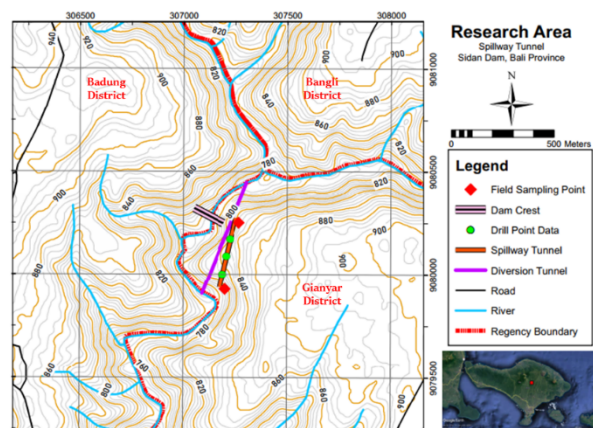


Fig. 2. Specified research area

2.1 Rock Mass Rating

The primary advantage of utilizing RMR is its simplicity and adaptability to various engineering applications [11]. The RMR approach classifies rock mass based on a total rating of six criteria (1) that can be determined in the field and interpreted using borehole data [1]. These criteria include the following: intact rock's Uniaxial Compressive Strength (UCS) (A1), Rock Quality Designation (RQD) (A2), discontinuity spacing (A3), discontinuity conditions (A4), groundwater conditions (A5), and discontinuity orientation (B). The rock support can be estimated from the value of RMR in the actual excavation using a designed excavation method and support table (for tunnels with a 10m span) [11].

$$RMR = A1 + A2 + A3 + A4 + A5 + B \quad (1)$$

2.2 Q System

Barton et al. (1974) developed the Q system for evaluating rock support in tunnels using a vast database of tunnel constructions. Six inputs (RQD = given as the value for this parameter; Jn = ratings for the number of joint sets; Jr = ratings for the joint roughness; Ja = ratings for the joint alteration, Jw = ratings for the joint or groundwater, and SRF = ratings for the rock mass stress situation) associated with the empirical equation (2) determine the value of Q. The rock support would be assessed using a practical design along with the ratio of the opening's span or wall height to the stability criteria for tunnel use (excavation support ratio, ESR) [12].

$$Q = RQD/Jn \times Jr/Ja \times Jw/SRF \quad (2)$$

2.3 Rock Mass Index (RMI)

The Rock Mass Index (RMI) is a volumetric parameter that indicates a rock mass's approximate uniaxial compressive strength, and for the jointed rock is expressed as the equation as shown below (3). σ_c = the uniaxial compressive strength of intact rock, jC = the joint condition factor, V_b = the block volume, JP = the jointing parameter [13].

$$RMI = \sigma_c \times JP = \sigma_c \times 0.2 jC \times V_b^D; (D = 0.37 jC^{-0.2}) \quad (3)$$

The RMI system for rock support employs distinct equations depending on whether the rock mass is discontinuous (jointed) or overstressed. In jointed rock or blocky ground, the RMI value is calculated on the basis of the influence of stresses (SL) and groundwater (GW) to characterize the ground condition factor (Gc) (4). Gc is linked with the geometrical or size ratio (Sr) (5) in the support selection chart. The rock bolt length was calculated using equations 6 and 7 [13]. Dt = diameter of tunnel; Db = block diameter; Wt = the wall height, Co = orientation of discontinuity set, and Nj = rating for the number of discontinuity sets.

$$Gc = RMI \times SL \times GW \quad (4)$$

$$Sr = Dt/Db \times Co/Nj \quad (5)$$

$$L_{b_{roof}} = 1.4 + 0.16 Dt (1 + 0.1/Db) \quad (6)$$

$$L_{b_{wall}} = 1.4 + 0.08 (Dt + 0.5Wt) (1 + 0.1/Db) \quad (7)$$

2.4 Geological Strength Index (GSI)

The GSI system classifies rocks according to two primary characteristics: their structure and surface conditions, which can be summarized in a simple diagram to ease field observations [14]. For subsurface's condition, GSI rating using the following (8) equation. JCond89 is the rating of discontinuity conditions from RMR Bienawski 1989.

$$GSI = 1.5 JCond89 + RQD/2 \quad (8)$$

2.5 Japan Society of Civil Engineering (JSCE)

JSCE system [3] involves seven variables: elastic wave velocity (km/sec), rock type, geological condition (effect of water and lithologic character, interval discontinuity, and condition of discontinuity), borehole core condition (RQD), the factor of competence, and tunneling situation and displacement standard [3]. The Ministry of Public Works and Public Housing of Indonesia also implemented this excavation planning and road tunnel strengthening system in mixed soil – rock

media guidelines [15]. The competence factor is calculated with a certain formula (9). qu = unconfined compressive strength (UCS) of the ground (kN/m^2), γ = unit weight of the ground (kN/m^3), and H = depth of cover (m).

$$\text{Competence factor} = qu/(\gamma \times H) \quad (9)$$

2.6 Assessing the excavation method and tunnel support system

This research has suggested an excavation method and tunnel support system based on an empirical methodology utilizing the defined table and charts of rock mass classification systems. The excavation was considered using the GSI [16], RMR, and JSCE systems, while the support system was assessed using the RMR, Q-System, RMI, GSI, and JSCE classification.

3 Results and Discussions

Field and laboratory observation indicate that the tunnel is located in the pyroclastic breccia rock unit (Figure 3), the Gunungkawi Ignimbrite Unit (Gki), with the following description: blackish, lapilli to block-sized (2-30 cm) angular lithic and scoria fragments, poorly sorted, matrix ash sized supported and fining upward. The upper part of this unit can be distinguished as tuff breccia as the proportion of matrix increases. UCS ranges from 2-21 MPa and dry unit weight 1.01-1.48 gr/cm^3 .

Rock masses were classified at five measurement locations using data from the outcrop on the tunnel portals and drilling data from three borings (BPS, BHT6, and BHT 7), as shown in Figure 4.



Fig. 3. Outcrop of slightly weathered pyroclastic breccia at the outlet of spillway tunnel

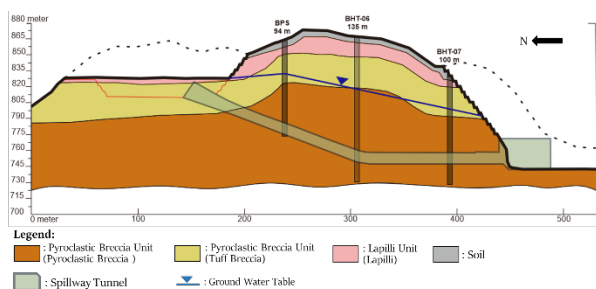


Fig. 4. Spillway tunnel lithology cross-section

3.1 Discontinuity and rock characterization

The findings of surface (2 portals inlet & outlet) and subsurface (73 face mapping of diversion tunnel, and three borehole data) examinations reveal the following properties of the pyroclastic breccia rock discontinuities surrounding the tunnel location: 1 set discontinuity (N200°E/740) and a random discontinuity (Figure 5), RQD value is approximately 19-30%, the dip angle is 55-83°, the spacing is 0.6 – 2m, slightly rough surfaces, separation <1mm, the walls are slight – highly weathered, and groundwater condition is wet – completely dry. UCS of pyroclastic breccia ranges from 2-21 MPa and dry unit weight 1.01-1.48 gr/cm³.

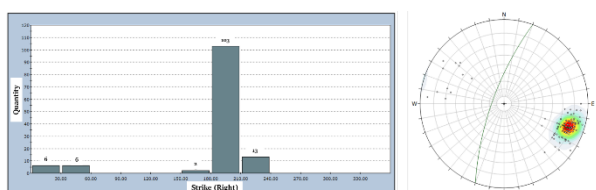


Fig. 5. Discontinuity's strike and dip orientation

The data shows that strike and dip of discontinuity orientation are very unfavorable for tunneling since the dip is more than 45° and the strike orientation is parallel to the tunnel axis [11]. These features are employed in the classification of rock masses.

3.2 Rock mass classification

RMR renders the use of six rating addition. According to the RMR system, the rock quality at the inlet portal is poor, whereas it is fair at other locations (Table 1). Q-system divides and multiplies variables (2). As per the Q method, the rock mass is classified as very poor to poor. (Table 2). The Q system conducts an analysis based on the location of the rock mass within the tunnel, for example, on the portal, so that it can make more precise recommendations for the portal's reinforcement system.

Table 1. Evaluation of the RMR system

No.	Location/ Borehole	UCS	RQD	Spacing	Condition	Groundwater	Orientation	Total Rating	RMR Class
1	Inlet	2	3	15	20	7	-12	35	Poor
2	BPS	1	8	15	20	10	-12	42	Fair
3	BHT 6	2	8	15	20	10	-12	43	Fair
4	BHT 7	2	8	15	20	10	-12	43	Fair
5	Outlet	2	8	15	20	10	-12	43	Fair

Table 2. Evaluation of the Q system

No.	Location/ Borehole	RQD	J _n	J _r	J _a	J _w	SRF	Rock Mass Quality (Q)	Q-System Class
1	Inlet	19	6	1	4	1	5	0.16	Very Poor
2	BPS	32	3	1	4	1	2.5	1.07	Poor
3	BHT 6	29	3	1	4	1	2.5	0.97	Very Poor
4	BHT 7	42	3	1	4	1	2.5	1.40	Poor
5	Outlet	34	6	1	4	1	5	0.28	Very Poor

RMi classification performs multiplication and exponential calculations simultaneously. Thus, supplementary calculations were performed on this system. As a result, rock mass classes range from medium to high (Table 3). The classification of rock masses based on GSI is accomplished in two ways: by observing the rock structure and degree of weathering at the tunnel portals on the surface and by performing conversion calculations on boreholes (Table 4). JSCE classifies rock mass in tunnels as CII or DII based on geological conditions, RQD, and estimation of competence factor (Table 5).

Table 3. Evaluation of the RMi system

No.	Location/ Borehole	σ _c	JP	RMi	RMi Class
1	Inlet	7.56	0.11	0.83	Medium
2	BPS	1.95	0.17	0.32	Medium
3	BHT 6	20.58	0.17	3.41	High
4	BHT 7	20.58	0.17	3.41	High
5	Outlet	20.58	0.17	3.41	High

Table 4. Evaluation of the GSI system

No.	Location/ Borehole	RQD	J _{cond}	GSI Rating	GSI Class
1	Inlet	-	-	25	Poor
2	BPS	32	20	46	Fair
3	BHT 6	29	20	45	Fair
4	BHT 7	42	20	51	Fair
5	Outlet	-	-	35	Poor

Table 5. Evaluation of the JSCE system

No.	Location/ Borehole	RQD	q_u	γ	H	Competence Factor	JSCE Class
1	Inlet	19	7560	9.904	35	21.81	C II
2	BPS	32	1952	14.513	73	1.84	D II
3	BHT 6	29	20580	14.513	108	13.13	C II
4	BHT 7	42	20580	14.513	69	20.55	C II
5	Outlet	34	20580	14.513	40	35.45	C II

3.3 Proposed excavation method

Using Tsiambaos and Saroglau's (2009) assessment of the tunnel excavation method, it is recommended that the excavation mechanism apply mechanical excavation in the form of digging excavation at outlets and inlets with relatively low GSI values and ripping excavations in sections with GSI values greater than 35 (Figure 6). The RMR and JSCE systems provide more detailed guidelines for excavation work based on the rock quality values in the surrounding area. Both systems underline the urgency of dividing the face of the tunnel into smaller sections during the excavation process using headings and benches.

Table 6. Determining rock excavation method based on RMR and JSCE

No.	Location/ Borehole	Excavation Method			
		Bench and cut		Meters in advance	
		RMR	JSCE	RMR	JSCE
1	Inlet	Yes	Yes	1-1.5	1.2
2	BPS	Yes	Yes	1.5-3	<1
3	BHT 6	Yes	Yes	1.5-3	1.2
4	BHT 7	Yes	Yes	1.5-3	1.2
5	Outlet	Yes	Yes	1.5-3	1.2

3.4 Proposed tunnel support system

The tunnel support system can be chosen empirically based on the quality of the rock mass, but multiple rock mass classifications are used to obtain a more convincing preference [1]. As per the RMR classification, poor rock requires systematic 4-5 m rock bolts spaced 1-1.5 m in the crown and walls with wire mesh, shotcrete thickness of 100-150 mm in the crown and 100 mm in the sidewall, and spaced 1.5 m light ribs where required. While fair rock is less reliant on reinforcement, i.e. systematic 4 m rock bolts spaced 1.5-2 m in the crown with wire mesh and walls, shotcrete thickness of 50-100 mm in the crown and 30 mm in the sidewall.

The guide charts were used to evaluate the tunnel support-based Q system [17] and RMi [1] (Figure 7 and Figure 8), where blue points refer to roof support and red points refer to wall support at each examination location. The value of the Excavation Support Ratio used in this analysis is 1. Q system wall support assessment uses a Q value multiplied by 2.5 and the tunnel height value instead of tunnel diameter. A reinforced rib of sprayed concrete (RRS) support is proposed at the inlet and outlet of the crown tunnel (Figure 7).

More numerical equations and calculations are required to determine tunnel support using the RMi classification than other rock mass classifications. The wall support is calculated by multiplying the value of G_c by 5 (adjustment factor roof and wall). Fibre and net reinforcement are also required at specific locations (Figure 8).

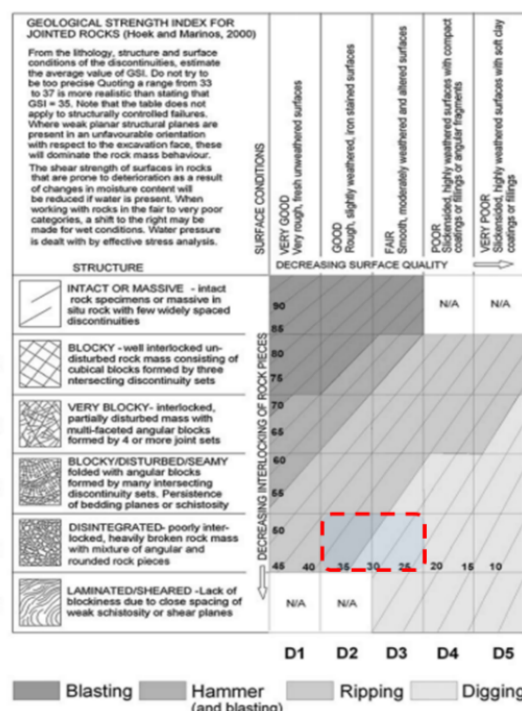


Fig. 6. Determining rock excavation based on GSI rating [16]

According to RMR classification, poor rock excavation will result in advances of 1.0-1.5 m in the top heading, while fair rock excavation will result in advances of 1.5-3.0 m in the top heading. On the other hand, JSCE recommends progressing tunnel excavation with a shorter distance than RMR, 1.2 m for class CII rock and < 1 m for class DII rock (Table 6).

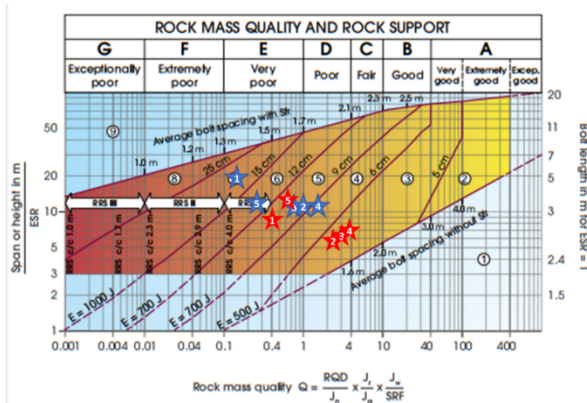


Fig. 7. Identification of tunnel supports based on the Q system [17]

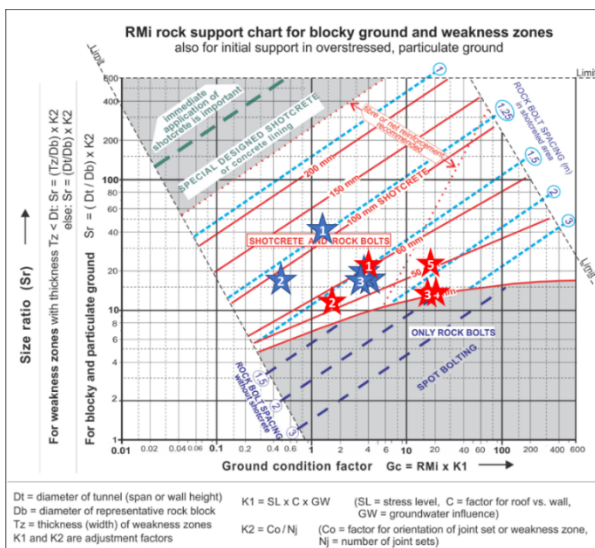


Fig. 8. Identification of tunnel supports based on RMI [1]

JSCE makes the following recommendations for structural support for DII class are rock bolt length 6 m, rock bolt spacing 1 m, area of installation top heading and bench, steel support: type H200 with 1 m spacing at top heading and bench, shotcrete thickness 25 cm and 40 cm lining. While for CII class are rock bolt length 4 m, rock bolt spacing 1.2 m, area of installation top heading and bench, steel support: type H150 with 1.2 m spacing at top heading, shotcrete thickness 15 cm and 40 cm lining.

Tables 7 to 9 contain rock mass classifications system recommendations for the tunnel wall and roof primary reinforcement system using shotcrete and rock bolts. The tunnel's crown shotcrete thickness varies between 60 and 200 mm, and wall shotcrete thickness varies between 30 and 400 mm. Moreover, the rock bolt spacing and length range from 2.6-6 m and 1-2.5 m for both roof and wall support of the tunnel.

The tables below indicate that, in comparison to other classifications, the JSCE classification provides recommendations for strengthening shotcrete with the highest total volume, followed by Q-System,

RMR, and RMI. This also applies to the recommended total length of rock bolt required; JSCE preferred a longer total length of rock bolt than other classifications. Supplemental tunnel support may result in more excellent safety and cost. However, in order to obtain the most efficient and appropriate quantity of tunnel support, further investigation is necessary to make adjustments to site conditions during excavation and tunnel detailed engineering design.

Table 7. The preferred thickness of shotcrete design

No.	Location/ Borehole	Support							
		Crown shotcrete thickness (mm)				Wall shotcrete thickness (mm)			
		RMR	Q-System	JSCE	RMI	RMR	Q-System	JSCE	RMI
1	Inlet	100-150	200	150	125	100	110	400	60
2	BPS	50-100	100	250	100	30	60	400	55
3	BHT 6	50-100	100	150	60	30	60	400	40
4	BHT 7	50-100	90	150	60	30	60	400	40
5	Outlet	50-100	130	150	70	30	110	400	55

Table 8. The preferred length and spacing of rock bolt design at roof support

No.	Location/ Borehole	Roof support							
		Rock bolt length (m)				Rock bolt spacing (m)			
		RMR	Q-System	JSCE	RMI	RMR	Q-System	JSCE	RMI
1	Inlet	4-5	5	4	4.5	1-1.5	1.3	1.2	1.1
2	BPS	4	4	6	3.3	1.5-2	1.7	1	1.25
3	BHT 6	4	4	4	3.3	1.5-2	1.6	1.2	1.5
4	BHT 7	4	4	4	3.3	1.5-2	1.8	1.2	1.5
5	Outlet	4	4	4	3.4	1.5-2	1.4	1.2	1.4

Table 9. The preferred length and spacing of rock bolt design at wall support

No.	Location/ Borehole	Wall support							
		Rock bolt length (m)				Rock bolt spacing (m)			
		RMR	Q-System	JSCE	RMI	RMR	Q-System	JSCE	RMI
1	Inlet	4-5	2.9	4	3.4	1-1.5	1.5	1.2	1.5
2	BPS	4	2.6	6	2.6	1.5-2	1.9	1	1.5
3	BHT 6	4	2.6	4	2.6	1.5-2	1.9	1.2	2.5
4	BHT 7	4	2.6	4	2.6	1.5-2	1.9	1.2	2.5
5	Outlet	4	4	4	3.0	1.5-2	1.6	1.2	1.75

4 Conclusions

According to the results of rock mass classification data, the rock mass quality at the inlet, which is included in the tuff breccia unit, is inferior to that of

the pyroclastic breccia unit. Therefore, the excavation process in the tuff breccia unit is considerably easier and requires more reinforcement than the tunnel in the pyroclastic breccia unit.

Digging and ripping are two tunnel excavation mechanisms that are suggested based on the GSI rating of the rock. It is advised that tunnel excavation be carried out utilizing the head and bench approach rather than the full excavation method. The JSCE proposes that excavation proceeds at a closer excavation distance (1-1.2 meters) than the RMR (1-3 meters), which may result in a slower excavation rate.

Each rock mass classification method recommended a mix of reinforced shotcrete and rock bolts for primary tunnel support, with varied shotcrete thickness (30-400 mm), rock bolt length (2.6-6 m), and rock bolt spacing (1-2.5 m). The prescribed designs were supposed to eliminate the uncertainty inherent in the empirical method and add to our understanding of tunnel design and construction safety. Implementing multiple rock mass classifications in tunnel construction planning can be used as a reference for designing other tunnels.

An empirical method for determining the excavation method and tunnel support is an excellent approach during the tunnel planning stage. However, other approaches, such as the 2D or 3D finite element method, are required to determine the displacement potential risk and tunnel safety factor under static and seismic loads, which is not considered in the empirical approach.

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