Rock Mass Characterizations and Kinematic Analysis for Construction Design Method of Diversion Tunnel of Dolok Dam, Central Java

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Abstract. Investigation of slope stability in the design of the tunnel portal is important to minimize slope failure. This research aims to describe the rock mass characterizations and classifications using Geological Strength Index (GSI) and Rock Mass Rating (RMR), along with the kinematic analysis and Slope Mass Rating (SMR) to define the risk of slope failure and the recommended support at the tunnel portal. Geological mapping and core evaluation were conducted to analyse the slope stability. The results show that the rock masses consist of intercalated rudstone with mudstone, typically have disintegrated, moderately disturbed, and blocky structures with slightly to highly weathered. The discontinuities have 3 – 4 sets consisting of bedding and joint, have medium to high persistence, close spacing, and dominantly have no infillings. These rock masses are classified as poor-fair rock in the upper part of the sequence, and good rock in the bottom part of the sequence. The kinematic analysis predicts the risk of toppling failure both in the inlet and outlet portal. The recommended support in the inlet portal is the combination of shotcrete, beams, and bolts, whilst in the outlet portal is the combination of surface drainage, shotcrete, dental concrete, beams, and bolts.
Keywords: Kinematic Analysis, Rock Mass Classification, Slope Stability, Support System, Toppling Failure

1 Introduction

Dolok Dam is one of the essential projects in the Central Java Region (Figure 1). It is now in the stage of planning and designing, including the design of the diversion tunnel. Geologically, the research area lies in Kalibeng Formation, consisting of mudstone in the bottom part of the sequence, then intercalated rudstone and siltstone in the center part of the sequence, and rudstone as the youngest lithology of the sequence. Dextral strike-slip fault was developed in this area, separating two structural hills with a North-South orientation [1, 2, 3]. This strike-slip fault mainly results in the development of joints that control the characteristic of rock masses in this research area.

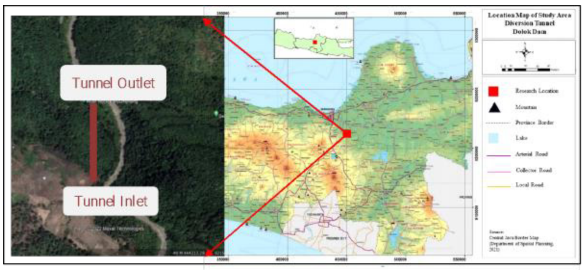

Figure 1. Location map of study area

The rock mass characterization can be obtained by classifying it into several categories according to its behaviours and properties along a tunnel, including slope stability analysis on the tunnel portal [4]. According to Norrish and Wyllie [5], there are two steps to analysing the rock slope stability. The first step is to analyse the discontinuities of the rock masses to see if their orientation could yield instability of the slope. This analysis used stereographic analysis, namely kinematic

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analysis. The second step is to count the factor of safety (FS), which can be obtained using a limit equilibrium analysis or finite element method (numerical analysis). In addition, the rock mass classification was empirically used to classify the rock masses. Two rock mass classifications were used in this study, namely Geological Strength Index (GSI) for heterogeneous rocks which was proposed by Marinos [6] and Rock Mass Rating (RMR) proposed by Bieniawski [7]. The stability of slope and recommendation of support system used in tunnel portal were analysed empirically using Slope Mass Rating (SMR) suggested by Romana [8].

Various researchers had published their work using similar slope stability methods. Nogkeaw, et al. [9] published their work on slope stability using the GSI system and stereographic projection in a quarry project, Thailand. Akram, et al. [10] investigated slope stability using kinematic analysis and SMR to evaluate rock cut slope in Pakistan. Juhari, et al. [11] evaluated the characteristics and classification of rock masses along road section in Yogyakarta, Indonesia.

Geological and geotechnical studies have been conducted for designing the stable slope of the inlet and outlet tunnel portal, but the description of the rock mass characterizations and classifications along with the kinematic analysis and SMR is limited. Therefore, this research plays a significant role to define rock slope potential failures and the recommended support system at the inlet and outlet of the designed tunnel portal.

2 Research Method

This research used fieldwork and laboratory tests to investigate rock mass characterization and classification. Surface and subsurface data were carried out, especially in the inlet and outlet location. Representative outcrops were used, located in the river adjacent to the tunnel. In addition, core data were also available in the inlet and outlet, which can be used as a data validation since the tunnel is still in the design stage. Kinematic analysis was used to predict the risk of failure both in the inlet and outlet portal by measuring the orientation of joint sets in the outcrops.

The characterization and classification of rock masses used GSI and RMR system. The modified GSI chart suggested by Marinos [6] was used to define rock mass quality since the heterogeneity of structures and compositions of the lithology in this research area is intercalated sandstone with siltstone and mudstone. The RMR classification developed by Bieniawski [7] was also used to fit up the description of joint conditions in outcrop and core data. Five basic parameters were used in the RMR system: Unconfined Compressive Strength (UCS) of intact rock, Rock Quality Designation (RQD), spacing between discontinuities, conditions of discontinuities, and groundwater condition. In addition, the total rating of RMR was also validated by the influence of discontinuity strike and dip orientation in tunneling. The UC*S* values were obtained by laboratory tests from outcrop and core data. The RQD values were calculated using two methods since there were surface data and core data. The RQD value from outcrop data was measured and calculated using the suggested Equation 1 proposed by Palmstrom [12, 13].

$$RQD = 115 - 3.3\,Jv \quad (1)$$

(RQD = 0 for Jv > 35, and RQD = 100 for Jv < 45)
Jv is defined as the number of joints intersection with a volume of 1 m^3. Equation 2, suggested by Palmstrom [12] was used to calculate Jv as the following:

$$Jv = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \cdots \frac{1}{S_n} + Nr/(5\sqrt{A}) \quad (2)$$

where S is the average spacings of the joint sets, Nr is the number of random joints, and A is the area in m^2. The RQD from core data was taken using Equation 3 as proposed by Deere and Deere [14].

$$RQD = \frac{\Sigma\, Length\ of\ core\ pieces > 10\ cm\ Length1}{Total\ length\ of\ core\ run} \times 100\% \quad (3)$$

The calculation of RMR from outcrop and core data is the total summation of five parameters explained above, shown in Equation 4.

$$RMR = R1 + R2 + R3 + R4 + R5 \quad (4)$$

In addition, GSI value from core data was taken by using a quantitative approach. Hoek et al. [15] had proposed a formula to calculate the *GSI* value from core data based on the description and rating from the joint condition and *RQD* data. The correlation between joint condition (*Jcond*) and *RQD is* as follows:

$$GSI = 1{,}5JCond_{89} + RQD/2 \quad (5)$$

Kinematic analysis was used in this research as a preliminary study of slope stability in inlet and outlet tunnel. The condition of discontinuities becomes very critical to be analysed since it represents the characteristic of rock masses. These discontinuities consist of bedding surfaces, joints, foliation, or other natural breaks in the rock [5]. Other than that, the strength of a rock mass is more dependent on the condition of discontinuities than on the properties of intact rock. There are five parameters for the description of the discontinuities that are similar to the description of joint conditions in RMR rating: orientation, persistence, spacing, surface properties, and infillings. Nogkeaw et al. [9] explain that kinematic analysis only uses the orientation of discontinuities (dip and dip direction) and the friction angle. However, it can still predict the stability of the risk of failures. In addition, the orientation of the discontinuities could result in instability of the slope [5]. This research examined the variation of risk failure based on stereographic projection.

The stability of a slope can be analysed empirically using SMR which was originally proposed by Romana [8]. Calculation of SMR can be obtained using four correction factors of basic RMR [7]. The value of SMR can be seen in the following expression:

$$SMR = RMR_b + (F1 \times F2 \times F3) + F4 \tag{6}$$

Where:

- RMR_b is the basic RMR from Bieniawski [7].
- F1, F2, and F3 are correction parameters of discontinuities and slope orientation.
- F4 is a correction factor which depends on the method of excavation.

3 Result and Discussion

3.1 Geology of the Study Area

Geological mapping was conducted to understand the geological processes that might work on the rock mass characteristics. Figure 2 shows the geological map and the geological cross section of the diversion tunnel and its surrounding area. The map shows that the average orientation of the rock is N 122° E with average dip is 45°. Structurally, there is dextral strike-slip fault which separating two hills. This fault might control the discontinuities or joints in the rock masses surround the river. It is proven by the condition of the discontinuities in the diversion tunnel and surrounding area which has blocky structure, formed by three to four joint sets.

There are four lithological units in the study area, sequentially from old to young started by mudrock unit, limestone or rudstone unit, interbedded mudrock with siltstone unit, and volcanic breccia unit. In can be seen in the map that the diversion tunnel lies on limestone unit, in more precise the facies of limestone based on petrography analysis belong to rudstone. The rudstone facies had coarsening upward sequence which is indicated by decreasing the composition of mudstone. At the outlet tunnel, the composition of mudstone is thicker than at the inlet tunnel. This stratigraphic feature has an implication on the quality of rock masses, which means the quality of rock masses at the outlet tunnel is lower than at the inlet tunnel as can be seen in the Table 3. From those interpretations, the characteristic and quality of rock masses in the diversion tunnel might be influenced by the stratigraphic and structural features which had been developed in the study area.

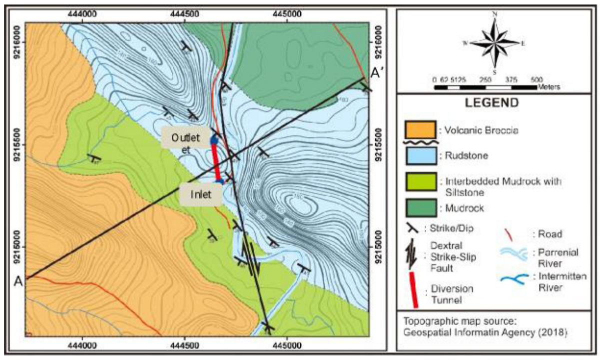


Figure 2. Geological map and geological cross section of the study area

3.2 Rock Mass Characterization

The characterization and classification of rock mass in this research were done using GSI and RMR. Both classifications were analysed and interpreted using representative outcrops for the surface data and core for subsurface data. The tabulation of rock mass characterizations and classifications at the inlet and outlet tunnel can be seen in Table 1. It also contains the orientation of discontinuities by dip and dip direction of bedding, join set on slope face, and the value of friction angle for kinematic analyses purpose. It can be seen that the GSI value obtained from the outcrop description and core evaluation was quite similar. In particular, the GSI description from outcrop data is presented in Table 2. The GSI value at the inlet outcrop showed the rock mass belong to type III which means there is a thin layer of soft material which is siltstone or mudstone on the sandstone layer. In the study area the thin layer is a mudstone which is intercalated with rudstone. The soft materials would decrease the quality of the rock masses as described in RMR analyses. On the other hand, the GSI value in the outlet outcrop showed that the rock mass belongs to Type IV, which means sandstone has a similar amount to siltstone in terms of its thickness, both were classified as fair rock. The differentiation between rock mass quality at the inlet and outlet tunnel is influenced by the stratigraphic features of the rudstone facies as explained in the previous chapter. Even though the GSI classification yielded the same quality as fair rock, but the value is slightly different. The GSI value in more detail will be used as an input in the numerical analyses for tunnel stability.

Table 1. The Characteristic of Rock Masses at the Inlet and Outlet Portal

Location	Data	Rock Mass Classification		Condition of Discontinuities				
		GSI	RMR	Bedding plane (B)/Joint set (Js) (Dip/Dip Direction)	Aperture (mm)	Spacing (m)	Persistenc e	Roughnes s
Inlet	Surface	Fair Rock	Fair Rock	B (51/224) JS1 (78/350) JS2 (75/35)	0,1 - 1	0,2 - 0,6	> 20m	Rough

	Subsurface	Fair Rock	Fair Rock					
Outlet	Surface	Fair Rock	Poor Rock	B (57/225) JS1 (81/342) JS2 (75/37)	0,1 - 1	0, 2 - 0,6	> 20m	Slightly Rough
	Subsurface	Poor - Fair Rock	Poor - Fair Rock					

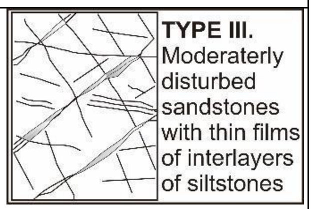
Location	**Data**	**Condition of Discontinuities**			
		Weathering	**Infillings**	**Ground Water**	**Friction Angle**
Inlet	Surface	Slightly Weathered	Soft filling < 5mm	Wet	50
	Subsurface				
Outlet	Surface	Moderately Weathered	Soft filling < 5mm	Wet	55
	Subsurface				

Table 2. The GSI Description Based on Representative Outcrop of Inlet and Outlet Portal

GSI at Inlet Portal

Photos



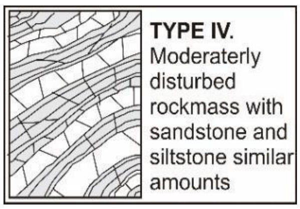



Description	GSI Value using GSI for heterogeneous rock masses [6] Type III. Moderately disturbed sandstones with thin films of interlayers of siltstone Surface condition is good: rough, slightly weathered
Rating	**50**
Classification	**Fair Rock**

GSI at Outlet Portal

Photos





Description	GSI Value using GSI for heterogeneous rock masses [6] Type IV. Moderately disturbed rock mass with sandstone and siltstone in similar amounts Surface condition: slightly rough, moderately weathered
Rating	**45**
Classification	**Fair Rock**

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One of the discontinuities parameters is joint wall surface, represented as surface roughness. This parameter is clearly seen from discontinuities of core data as shown in Figure 3. Figure 3-a is core data from BH-2 (Inlet). The joint wall surfaces appear as undulating and rough. On the other side, Figure 3-b showed the joint wall surface appearance of BH-3 (Outlet) as undulating and slightly rough. This slightly rough appearance is because the grain size of the sandstone in the outlet is relatively smoother than in the inlet. In line with the GSI value, the RMR value was more pessimistic, especially in the outlet location. The comparison can be seen in Table 1, the RMR value in outlet location resulted poor rock – fair rock, even though it did not give any different value in the inlet location. The pessimistic value in outlet location was also recognized from the GSI description, since it gave type IV classification, means that the rock mass characterization was poorer than in the inlet location.

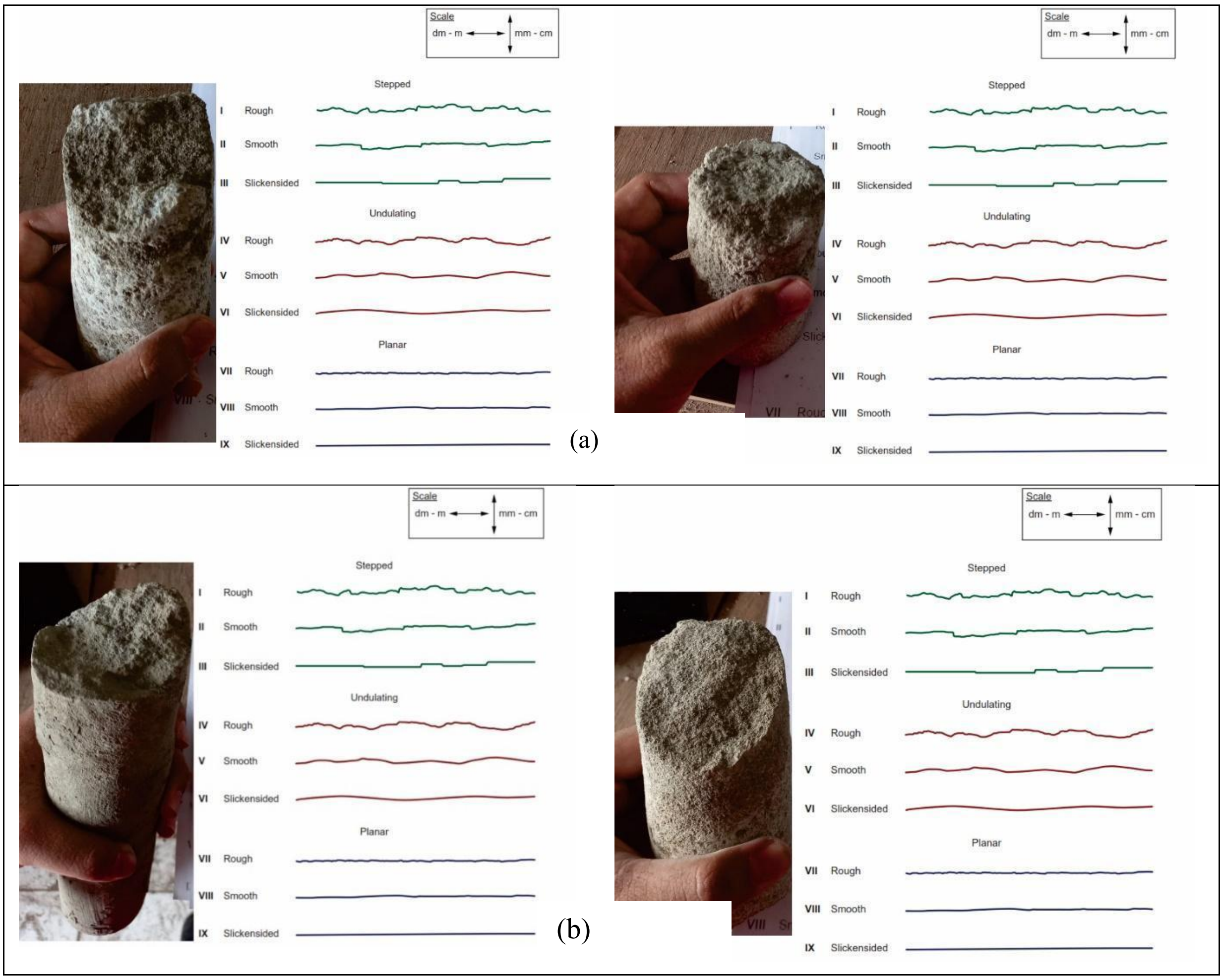

Figure 3. Roughness condition from core data

3.3 Kinematic Analysis

This research used stereographic projection for kinematic analysis of the slope. The results of the analysis are shown in Figure 4. The risk of failure of the inlet and outlet slope was investigated through DIPS 7.0 computer program. Table 3 shows the possibility of all risk failures based on kinematic analysis using DIPS 7.0 program. The kinematic analysis resulted in the risk of failure both at the inlet and outlet slope as toppling, specifically flexural toppling, and oblique toppling as shown in Figure 4. According to Goodman and Bray [16], toppling failure is formed by the discontinuities (bedding planes and joints) which have a parallel strike orientation to the slope crest and dip into the rock mass, and usually occur in columnar rock. Specifically, flexural toppling will occur when the maximum tensile stresses in each rock column exceed its tensile strength [17]. In addition, flexural toppling can occur due to interlayer slip, which releases the columns to bend in flexure [16].

Table 3. Risk failure possibility in the inlet and outlet slope

Location	Possibility of Risk Failure			
	Planar Failure	Wedge Failure	Flexural Toppling Failure	Direct Toppling Failure
Inlet	0%	0%	38.46% on JS1	29.63% as Oblique Toppling with 46.67% baseline is on Bedding Plane
Outlet	0%	0%	50% on JS1%	32.14% as Oblique Toppling with 27.78% baseline is on Bedding Plane

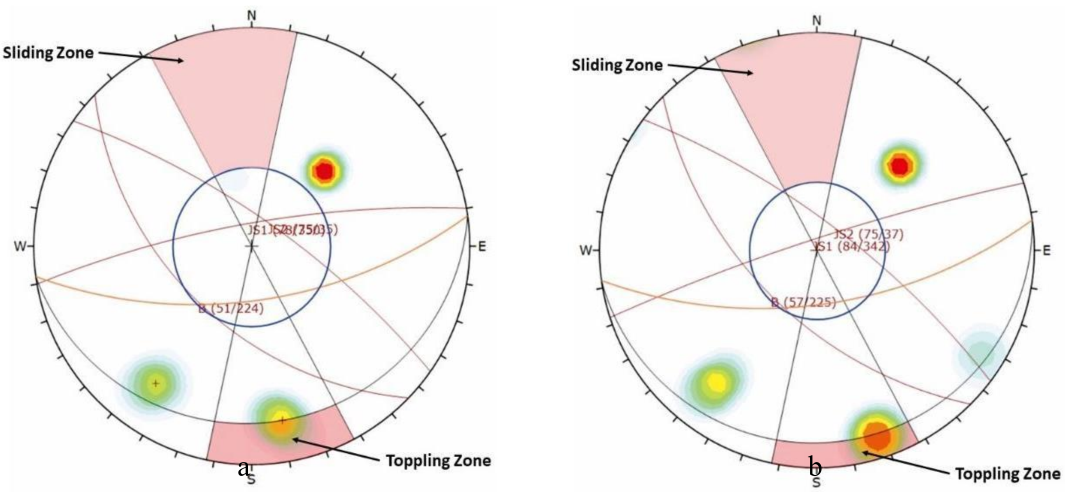

Figure 4. Kinematic analysis of the inlet (a) and outlet slope (b)

The kinematic analysis resulted from DIPS 7.0 program must be manually validated to some conditions as described by Norrish and Wyllie [5] for planar, wedge, and toppling failure. Table 4 shows the simplified summary of necessary conditions that must be fulfilled for each failure. The required conditions of each failure must be fulfilled to make failure occur, not all risks of failure will occur even though the DIPS 7.0 application suggested the failure.

Table 4. Possibility of failure in accordance with the required conditions

<table>
<tr><td>(a)</td><td colspan="3">INLET</td></tr>
<tr><td></td><td>Planar Failure</td><td>Wedge</td><td>Toppling</td></tr>
<tr><td>Possibility</td><td>X</td><td>X</td><td>√</td></tr>
<tr><td rowspan="3">Reason</td><td rowspan="3">The direction of dip in the planar discontinuity is greater than 20 degrees</td><td rowspan="3">There is no intersection of joints in front of the slope face</td><td>The strike of the discontinuities is parallel to the slope face</td></tr>
<tr><td>The dip of the discontinuities is opposite to the dip of slope face</td></tr>
<tr><td>Interlayer slip occur
$(90^{\circ}-\Psi p) \leq (\Psi f-\phi p)$ $(90-62) \leq (78-50)$</td></tr>
</table>

<table>
<tr><td>(b)</td><td colspan="3">OUTLET</td></tr>
<tr><td></td><td>Planar Failure</td><td>Wedge</td><td>Toppling</td></tr>
<tr><td>Possibility</td><td>X</td><td>X</td><td>√</td></tr>
<tr><td rowspan="3">Reason</td><td rowspan="3">The direction of dip in the planar discontinuity is greater than 20 degrees</td><td rowspan="3">There is no intersection of joints in front of the slope face</td><td>The strike of the discontinuities is parallel to the slope face</td></tr>
<tr><td>The dip of the discontinuities is opposite to the dip of slope face</td></tr>
<tr><td>Interlayer slip occur
$(90^{\circ}-\Psi p) \leq (\Psi f-\phi p)$ $(90-62) \leq (84-55)$</td></tr>
</table>

3.4 Slope Stability and Support System

The slope mass rating method from Romana [8] was used to predict stability and support recommendations for the slope. Table 5 summarizes modes of failure, RMR value, Rock classification, SMR value, stability, and support recommendation of inlet and outlet slope. The stability of the slope in the inlet and outlet tunnel is quite different, this will affect the recommended support system. The result of this empirical analysis can be used as a reference in the preliminary study and has to be validated precisely using analytical and/or numerical method using Limit Equilibrium Method (LE) and/or Finite Element Method (FEM).

Table 5. Stability of the Inlet and Outlet Slope based on SMR

Location	Modes of failure	RMR Class	SMR	SMR Class	Stability	Recommended Support
Inlet	Toppling	Fair Rock	42	Normal	Partially stable	Shotcrete, beams, bolts
Outlet	Toppling	Poor Rock	37	Bad	Unstable	Surface drainage, shotcrete, dental concrete, beams, bolt

4 Conclusion

Rock mass characterizations and classifications using Geological Strength Index (GSI) and Rock Mass Rating (RMR), along with kinematic analysis and Slope Mass Rating (SMR) had been successfully defined the risk of slope failure and the recommended support at the portal of diversion tunnel of Dolok Dam. The results indicate that the rock mass characteristic of the inlet portal and outlet portal is slightly different. The rock masses in the inlet portal consist of intercalated rudstone with thin layer of mudstone, whilst the outlet portal has thicker mudstone. This condition will affect the quality of the rock masses. The quality value based on GSI in the inlet portal is 55, classified as Type III, whereas in the outlet portal is 50, classified as Type IV, both belong to fair rock. Based on RMR, the rock masses in the inlet portal are classified as fair rock, and in the outlet portal are classified as poor rock.

Kinematic analysis indicates that the risk of flexural toppling and oblique toppling failure may occur at the inlet portal and outlet portal. Based on SRM, the recommended supports at the inlet portal are the combination of shotcrete, beams, and bolt, whilst at the outlet portal are the combination of surface drainage, shotcrete, dental concrete, beams, and bolts. Further studies are therefore necessary to determine the effect of recommended support system by calculating the safety factors of the slopes.

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