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ESTIMATING THE RADIAL DISPLACEMENT ON THE TUNNEL BOUNDARY BY ROCK MASS CLASSIFICATION SYSTEMS

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ABSTRACT: RMR classification of rock masses was developed based on a great number of practical cases in tunneling by Bieniawski in 1973. RMR illustrates instructions of the design of support and stand-up time of the tunnel. In Russia, there is a rock classification for the stability of rock masses surrounding the horizontal tunnels that have been developed by VNIMI and are included in design standards (SNiP II-94-80 Underground Mine Workings). In this paper, the relation between RMR, VNIMI's classification, and Radial Displacement (RD) was surveyed by using RS2 software (Rocscience). Geology conditions of Ialy Hydropower Plant Expansion Project, Viet Nam for D shaped circle and horseshoe tunnel is adopted as a reference case. The tunnel stability was estimated by the Radial Displacement (RD) determined at some vital points of the typical tunnel boundaries that allow predicting the stability of the tunnel after being supported.

Keywords: RMR, Tunnelling, VNIMI's classification, Stability, Radial Displacement

1. INTRODUCTION

Rock mass classifications are widely used in engineering for the preliminary design purpose. It represents a powerful tool for estimating rock mass stability, selecting underground support systems, and predicting behaviour of rockmass. Tunnel designers take advantage of the geomechanical classification of rocks RMR by Bieniawski [1], along with this, there are correlation dependences between the parameters of RMR and GSI [1, 2].

The geomechanical RMR classification of a rock mass (1973) was based on the experiments Bieniawski carried out in South Africa [1]:

$RMR = R_{bs} + R_{RQD} + R_{dj} + R_w + R_{cj} + R_{oj}$;

where *RMR* is the rock mass rating; R_{bs} is the rating for uniaxial compression strength of rock; R_{RQD} is the rating for rock quality designation; R_{dj} is the rating for joint spacing; R_w is the rating for water condition; R_{cj} is the rating for the joint condition; R_{oj} is the rating for joint orientation. The RMR-classification of rock masses is presented below (Table 1).

Table 1. RMR- Classification of Rock Mass [1,2]

Class of rock mass	I	II	III	IV	V
RMR	100 -81	80-61	60-41	40 – 21	< 20

A rock classification for the stability of rock masses surrounding horizontal workings has been developed by VNIMI in Russia and is included in design standards (SNiP II-94-80 Underground Mine Workings) [6,7].

(Rahmannejad, R., & Mohammadi, 2007) carried out the comparison of the most widely-applied rock-mass classifications RMR and Q and a system developed by VNIMI's classification rock mass in Russia. It showed that the results obtained from using these systems for the forecast of rock mass stability and selection of support types enjoy satisfactory conformity. However, the authors just mentioned the type of shape of a tunnel [7].

Recent previous studies mainly focus on finding the relationship between GSI and RMR by theoretical analysis method, or field experimental method [10, 11, 12, 13, 14, 15].

This study aims to compare the classifications RMR and that of VNIMI. Geology conditions of Ialy Hydropower Plant Expansion Project, Viet Nam for D shaped circle and horseshoe tunnel are adopted. The rock mass stability and the recommended support type are identified.

The stability of rock mass is estimated based on the Radial Displacement (RD) value of tunnel boundary obtained from numerical models by RMR and VNIMI's classification rock mass. The performance research would significantly contribute to RMR application in tunneling, especially in predicting the stability of a tunnel. Research results allow evaluating the radial displacement on the tunnel boundary within the RMR and VNIMI's classification at Ialy Hydropower Plant Expansion Project in Vietnam.

2. GEOLOGICAL STRENGTH INDEX (GSI)

The Geological Strength Index (GSI) is a rock mass characterization tool developed for the design of tunnels, caverns, and other underground structures based on field observations including geological data about rock mass, inputs from qualified and expert field geologists. Engineers about the visual impression of the rock structure including block and surface condition of the discontinuities represented by joint characteristics (roughness and alteration) and providing reliable data in the form of rock mass strength properties which are used as input parameters for numerical analysis or closed-form solutions. The GSI classification system has gained wide acceptance as an empirical tool for estimating the strength and deformation characteristics of heavily jointed rock masses [11].

The GSI system, as compared to other rock mass classification systems, may represent the heterogeneity of rock mass conveniently in terms of rock mass structure domain (Rehman, H., 2020) [11,12]; (Campos et al., 2020) [3].

One of the requirements of rock support is to ensure the stability of the tunnel. Although rock support was framed followed instructions by empirical methods of RMR, the weakness of RMR is the fact that the stability of the tunnel was not quantified. One of the explicit behaviors of tunnel stability is the displacement of the tunnel boundary. Normally, the displacement of the supported tunnel boundary reflects the instability of rock mass surrounding the tunnel. In reality, displacement is usually determined by convergence measurement method of by extensometer installed in the rock mass. Unfortunately, the Radial Displacement (RD) degree on the tunnel boundary within RMR value and VNIMI's Classification of Rock has not been taken into account adequately.

To solve the problem, the author conducted a numerical investigation using RS2 software [4] to determine the stability of the tunnel in terms of radial displacement (RD) measured at two points on the tunnel boundary, which are (1) the crown of the tunnel; and (2) tunnel floor (see Fig. 1).

3. CASES STUDY AND NUMERICAL MODEL

3.1. The Ialy Hydropower Plant Expansion Project

Ialy Hydropower Plant Expansion Project, which is invested by Vietnam Electricity (EVN), will be built 400m away from the existing operating Ialy Hydropower Plant (720MW). The project site is located in Ya Tang commune (Sa Thay district, Kon Tum province, Viet Nam) and Ia Mo Nong commune, Ia Kreng, Ialy town (Chu Pah district, Gia Lai province). The old Ialy hydroelectricity was built in 1993 with the help of Russia. Ialy Hydroelectricity has an installed capacity of 720 MW with 4 units, the average annual electricity is 3,650 million KWh [9].

It is very important to be implemented Ialy Hydropower Plant Expansion Project to ensure the principle that all the components of the existing Ialy Hydropower Plant shall be kept intact. The design and construction of the new energy tract and the new plant shall be on the left side of the existing energy tract and shall be independent of the other items of the existing Ialy Hydropower Plant, including main items such as channels to water intakes, water intakes, water tunnel, pressurized tower, penstocks, power plant, downstream discharge channel and the system connecting the plant to the national power system, and so on. Rock mass parameters applied in this study were shown in Table 2.

A rock classification for the stability of rock masses around horizontal workings of VNIMI and design standards (SNiP II-94-80 Underground Mine Workings) is presented in Table 2.

Table 2. VNIMI's classification of rock [1,2]

Mass Rock stability Category	Rock state	Displacement, mm		
		Sedimentary rocks	Igneous rocks	Salt rocks
I	Stable	Up to 50	Up to 20	Up to 200
II	Medium-stable	From 50 to 200	From 20 to 100	From 200 to 300
III	Unstable	From 200 to 500	From 100 to 200	From 300 to 500
IV	Strong-unstable	Exceeds 500	Exceeds 200	Exceeds 500

The effect of gravity on the initial stress-induced in rock mass was taken into consideration. In this study, the depths of the tunnel are 58, 90, and 200m with different RMR values respectively. The lateral earth pressure (K_0) was calculated by the formula (1) [8]. The rock's unit weight (γ), uniaxial compressive strength, disturbance factor are presented in Table 2 respectively.

$$K_0 = 0.25+7E(0.001+1/H) \quad (1)$$

Table 3. Rock mass properties [9]

N^0	Rock Properties	Unit	Class		
			IB	IIA	IIB
1	Rock name	-		Granite	Gneis
2	Rock's unit weight (γ)	MN/m^3	0.026	0.0271	0.0273

3	Uniaxial compressive strength (σ_{ci})	MPa	30	69	89
4	Depth of tunnel (H)	m	58	90	200
5	Q	-	7;8; 9;10	15; 20; 25; 30; 35; 40	45; 50; 55; 60
6	RMR	-	41-60	61–80	80-100
7	Lateral earth pressure (K_0)	-	0.7616	0.8434	0.628
8	Poisson's ratio (μ)	-	0.3	0.25	0.21
9	Disturbance factor (D)	-	0	0	0

Table 3 gives the outcomes of these classifications for 10 of the 79 variants considered. Each variant corresponds to the specific geological zone of a design.

3.2. Evaluation of rock mass and rock support parameters

The constitutive model using the Hoek-Brown failure criterion has been adopted for the rock mass surrounding the tunnel [8]. The deformation modulus of intact rock E_i was evaluated as follows [9]:

$$E_i = MR.\sigma_{ci} \tag{2}$$

Where: MR - Modulus ratio, MR = 500; σ_{ci} - Uniaxial compressive strength, σ_{ci} = 50 MPa.

The deformation modulus of rock mass (E_{rm}) was calculated on the basis of the following relationship:

$$E_{rm} = E_i\left(0.02 + \frac{1 - D/2}{1 + e^{((60+15D-GSI)/11)}}\right) \tag{3}$$

Where: D - Disturbance factor, assumed D = 0; GSI - Geological Strength Index.

The reduced value of material constant (m_b) was calculated based on the Hoek - Brown failure criterion [8]:

$$m_b = m_i.\exp\left(\frac{GSI - 100}{28 - 14D}\right) \tag{4}$$

Where: m_i - Material constant.

It should be noted that Table 2 just adopts the RMR value. Bieniawski [1, 2] introduced a relationship between the GSI value and Rock Mass Rating (RMR) value of rock mass as follows:

$$GSI = RMR_{89} - 5 \tag{5}$$

RMR_{89} - rock mass rating according to Bieniawski (1989) when the groundwater rating = 15 and joint adjustment rating = 0.

These parameters were determined according to rock mass parameters in Table .

In this study, GSI was determined according to the study result of (Rehman, H. et al, 2020) [12]

$$GSI = 0.9143RMR + 6.132 \tag{6}$$

Moreover, the parameters of bolts used in models were illustrated in Table 4.

Table 1. Rock support properties (Data of Electricity Construction Consulting Joint Stock Company 1) [9]

Properties	Unit	Value
Fully Bonded Bolts		
Bolt Diameter	mm	20
Bolt Modulus (E)	MPa	200000
Tensile Capacity	MN	0.5
Residual Tensile Capacity	MN	0.5
Pre-Tensioning Force	MN	60
Bolt length (L)	m	2.7

It is noted that the bolt length and bolt spacing are picked from RMR.

The bolt length is equal to all cases at 2.7m due to the same Equivalent Dimension (De) value, however, there is an increase from 1.8m to 3.33m in bolt spacing by RMR values from 41 to 100 (Table 5).

Table 5. Support Type: Bolt spacing (S), L = 2.7m

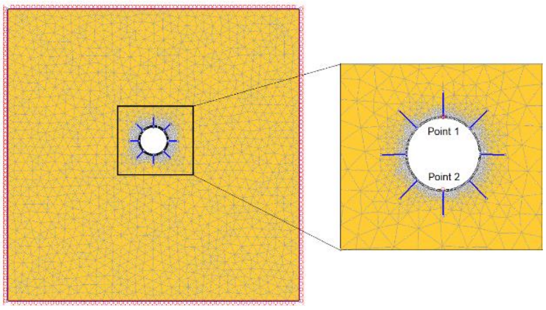
RMR	41	47	53	60	61	65	69
S (m)	1.8	1.87	1.93	2.0	2.17	2.3	2.5
RMR	73	77	80	81	87	93	100
S(m)	2.67	2.83	3.0	3.08	3.17	3.2	3.3

3.3. Numerical model

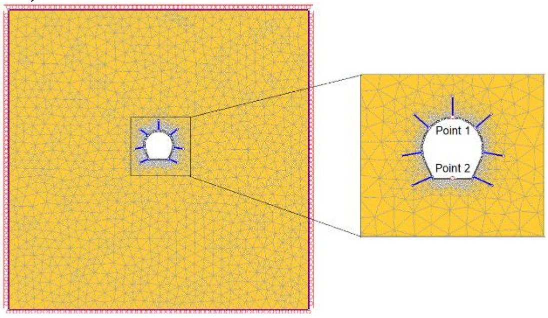
In reality, tunneling is a complicated three-dimensional (3D) issue depending on the advance of the tunnel face. However, the tunnel considered in this study has a length that is much larger than the dimensions in the cross-section of the tunnel. For the sake of simplicity, a two-dimensional (2D) model could therefore be used instead of a 3D model [7].

The numerical model is carried out for the cases of circle, horseshoe, and D tunnel shapes (see Fig.1) applied in the Ialy Hydropower Plant Expansion Project, Vietnam. They have the same maximum span of 7.8m.

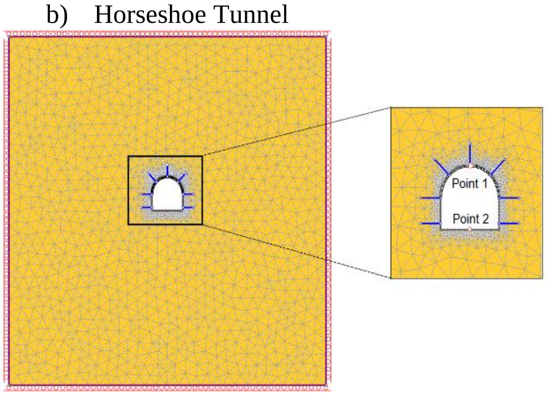
The numerical model was discretized and meshed into finite elements. Finite elements in the model were formed as triangles with 6 nodes. Since the model size was enough large to eliminate the effect of model size on the stress and displacement in the rock mass surrounding the tunnel. The external boundary of the model was restricted in X and Y directions, respectively (Fig.2).



a) Circle tunnel



b) Horseshoe Tunnel



c) D- shape

Fig. 1. The layout of the numerical model and monitored points (1), (2) was determined by the vertical displacement at point (1), (2) for a) Circle shape; b) D-shape; c) Horseshoe cross-section tunnel

4. RESULTS AND COMPARISON

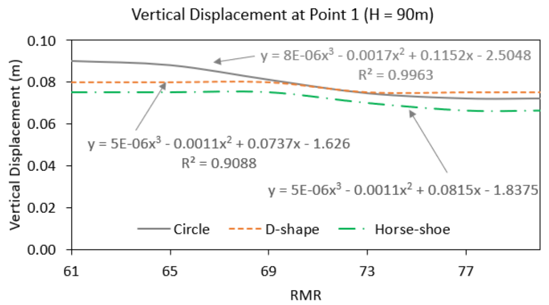
4.1. Radial displacement on tunnel boundary in RMR

Overall, it is clear that there is a downward trend in the relationship between RD and RMR value at points 1 and 2. In the other words, on the condition that the rock mass quality increases, the tunnel stability shows a sign of more stability, however, there was a significant increase of RD when RMR value is over 80 at both observation points due to the great rise of tunnel depth. Vertical Displacement for type rock IIA (RMR = 61 -80) at H = 90m is described in Fig 2. Radial Displacement (RD) at Point 1 and Point (2) in different tunnel depths and RMR values is presented in Fig.3.

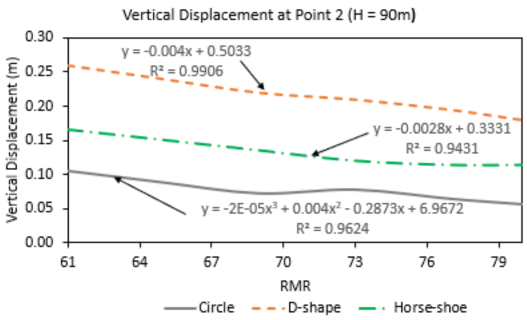
Take the circle shape as an example, the highest RD at point 1 is at 0.12m (RMR = 41) and just under 0.08m is the lowest one (RMR = 80), but this figure sharply rises to 0.1m when the RMR value is over 81.

Another point worth mentioning is that the RD at point 2 is higher than that of Point 1 in almost all cases since bolts are not applied on the floor of a D shape and Horseshoe (see Fig. 3).

In addition, at point 1, the discrepancy in terms of RD between cross-section types is inconsiderable and the order of them is not clear.



a) Vertical displacement including support for type rock IIA (RMR = 61 -80) at point (1)

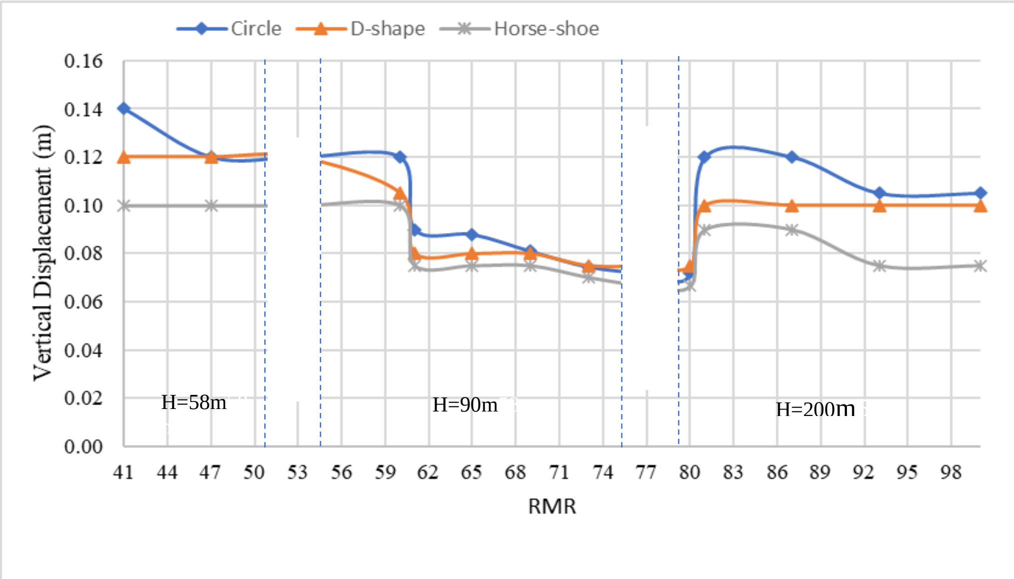


b) Vertical displacement including support for type rock IIA (RMR = 61 -80) at point (2)

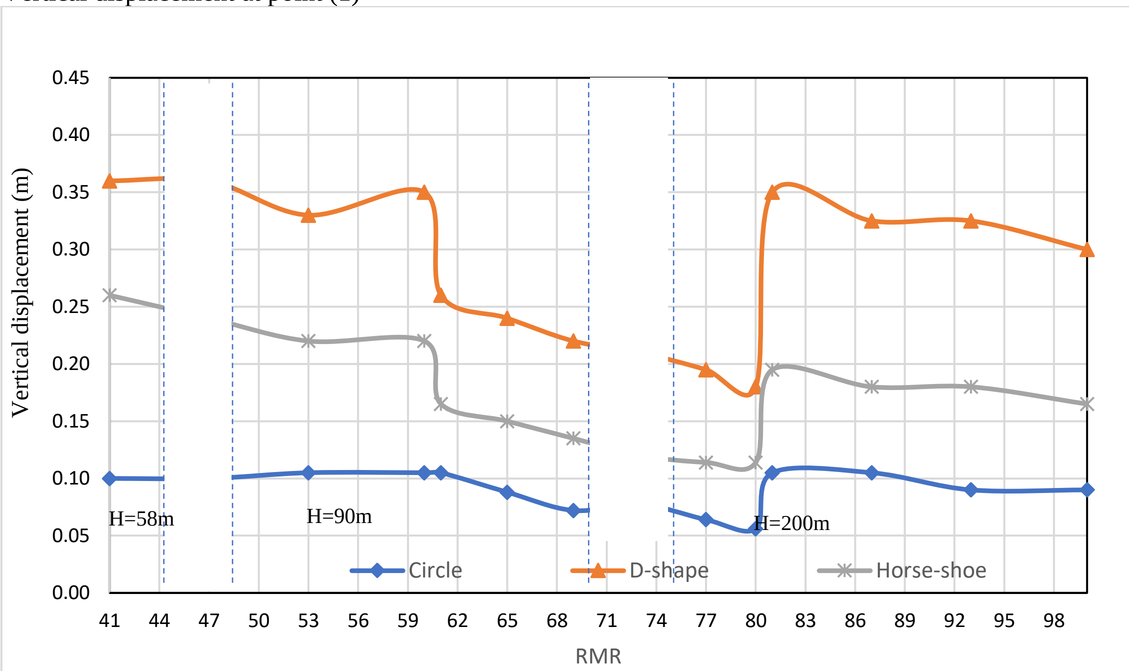
Fig. 2. Vertical Displacement for type rock IIA (RMR = 61 -80)

On the contrary, a clear order is witnessed between cross-section types at point (2). To be specific, the RD of the D shape is always the highest and the RD of Circle shape hits the lowest point at all RMR values. This could be easily demonstrated that the flat floor is the most unstable in comparison with circulars and the horseshoe shape is less unstable than the D shape due to the shorter flat floor and curve wall that trigger more harmonized stress in the rock mass.

Furthermore, the discrepancy between them at point (2) is more and more significant when the RMR value increases.



a) Vertical displacement at point (1)

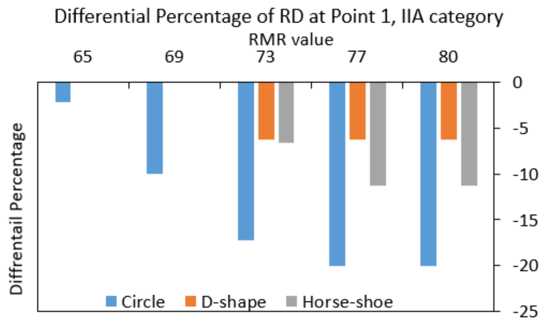


b) Vertical displacement at point (2)

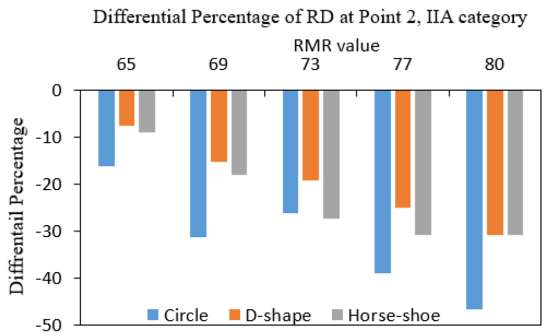
Fig. 3. Radial Displacement (RD) at Point 1 and Point (2) in different tunnel depths and RMR values

To get more details about the difference RD between RMR values in IIA categories, Figure 4. Illustrates the decreasing percentage of RD at point 1 in three types of tunnel boundary. The decreasing percentage of RD was calculated by differential value in percentage between RD of RMR (at 65, 69, 73, 77, and 80) and that of RMR (61).

Overall, the differential percentage of RD is directly proportional to the RMR value. In other words, when the rock mass quality increases, the RD shows the sign of decrease that makes the differential percentage of RD surge. Moreover, the magnitude of differential percentages at point (2) is greater than that of point (1). This is mainly caused by the less stability of the floor. Additionally, the differential percentage of RD of circle shape is always highest, followed by D shape and horseshoe, due to the quick response of decreasing RD on the circle boundary than others.



a) Differential Percentage of RD at point (1), IIA category



d) Differential Percentage of RD at point (2), IIA category

Fig 4. The differential percentage of RD at point 1 and point (2), IIA category

4.2. Comparison

In this section, the study compared displacement values on the tunnel boundary for different types of tunnel shapes on the basis of data collected from the Italy hydropower project. There were several geological zones along the headrace tunnel, and we managed to get 3 types of different geological zones in IB, IIA, IIB rock types by VNIMI's classification.

Some of them already possess the stability class determined by RMR values. We found the stability classes and support types by RMR values for the rest zones and also the stability classes by VNIMI classifications for all the geological zones of the Ialy Hydropower Plant expansion project. The comparison results in terms of classifications by RD are presented in Table 6.

Table 6. Comparison of the Radial Displacement (mm) at Point 1

N^0	Type of rock according to the VNIMI's classification	VNIMI's classification	RMR	Percentage of difference
1	IB	73.44	113.75	54.89%
2	IIA	42.84	76.14	77.73%
3	IIB	18.36	98.33	435.58%

Statistics have shown that the average RD in RMR is more likely higher than that of VNIMI's classification. The smallest and highest differences are observed in rock mass IB and IIB, respectively. This difference could be demonstrated that the RMR in this paper would be applied for the Ialy Hydropower Plant expansion project only, with three classes of rock mass (IB, IIA, and IIB) and three types of the boundary, however, the figures for RD of VNIMI's classification were collected more largely.

5. CONCLUSION

In this paper, a numerical investigation has been conducted to estimate the Radial Displacement (RD) induced on the tunnel boundary. Some conclusions could be derived as follows:

- An instruction of estimating the stability for supported tunnels in terms of RD based on rock mass classification systems applied for D shaped, circle and horseshoe tunnel, has been introduced. This allows preliminarily predicting the behavior of tunnel at the design phase;
- There was an inverse proportion between RD and RMR values at both observation points and the discrepancy of RD among boundary types at point (2) was larger than that at point (1) with clear orders.
- The differential percentage of RD was analyzed with the highest differential percentage belonging to a circle shape and greater differential percentage at point (2).
- This paper also made a comparison between VNIMI's classification and RMR in terms of RD. The results showed that RD's RMR was higher than that of VNIMI's classification at three classes (IB, IIA, and IIB).
- Additional numerical calculation and in-situ measurement are necessary to be conducted to enlarge the estimate of the behavior of the supported tunnel using RMR and VNIMI's classification for other tunnels with different shapes and dimensions.
- The comparison of the outcomes of the rock mass classifications by VNIMI, RMR yields a satisfactory degree of coincidence between the forecast of rock mass stability and the support type selected.
- The difference in the estimates obtained from the classifications discussed seems to be related to the fact that the classification systems independently select the main factors and take into account the rating of parameters.

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