www.gondwanags.org.in

Research Article

ISSN : 2455-1953

JGSR

*Journal of Geosciences Research*
*Vol. 8, No.2, July, 2023, pp. 118-126*

# Rockmass Characteristics and its Influence on TBM Penetration Rate in Archeans and Meta-sedimentary Rocks of India

D. Ramakrishna[1*,2] and N. Rajeshwara Rao[2]

*[1*,2]Dr.M.G.R. Educational and Research Institute, Maduravoyal, Chennai-600095(TN), India*
*[2]Department of Applied Geology, University of Madras, Guindy Campus, Chennai-600025(TN), India*
*(*Corresponding author, Email: devalla.ram@gmail.com)*

## Abstract

TBM penetration rate prediction models were developed for the hard Archean granites, granite gneisses and Meta-sedimentary rock groups comprising of quartzites, quartz arenites and sandstone of peninsular India.Construction stage engineering geological mapping comprising of face logging resulted in rockmass characterisation of Archeans and Meta-sedimentary rock groups. Statistical correlation of TBM penetration rate (PR) with Rock quality designation (RQD), unconfined compressive strength (UCS), volumetric joint count (Jv) and rockmass class was carried out. The prediction model provides good correlation only in the Meta sedimentary rock group for RQD, UCS and rockmass class and good correlation only for RQD and rockmass class in the Archean group but poor correlation with UCS. There is an exponential increase of penetration rate with Jv in both the rock groups.

*Keywords:* TBM Penetration Rate, Rockmass Characteristics, Geological Mapping, Rockmass Classification, Rock Tunnel

## Introduction

One of the key challenges of excavation by Tunnel Boring Machine (TBM) in hard rock is the prediction of reliable penetration rates, which is often a decisive factor in the overall cost of the project. Though various borability models were developed by researchers (Rostami and Ozdemir, 1993b-c; Bruland, 1998; Barton, 1999; Bieniawski *et al.*, 2007; Yagiz, 2008; Gong and Zhao, 2009), each model has its own specific limitations on geology and is not universally applicable.

In rock tunnels, important factors governing TBM excavability are rockmass characteristics, machine variables and efficiency of operator. Two of the currently most recognized TBM performance prediction and prognosis models in use around the world are the Colorado School of Mines (CSM) (Rostami and Ozdemir, 1993; Rostami, 1997) and Norwegian University of Science and Technology (NTH) models (Blindheim, 1979; Bruland, 1998). CSM model for TBM performance prediction was based on the force equilibrium method and involves measurement and evaluation of cutting forces on an individual cutter (Rostami and Ozdemir, 1993b-c). The estimate of cutting forces is provided by full scale cutting test. This model uses rock property values such as UCS and Tensile strength and combined with cutter geometry and cutter information, gives an estimate of the cutting forces. This model does not take the rockmass properties into account and the effect of grain size, hence applicable only for massive rocks. NTH developed an empirical model by considering intact rock, rockmass properties and machine parameters (Lislerlud, 1988; Bruland, 1998) and are based on the historical field performance of TBMs in certain rock types. The models are a set of empirical graphs and equations between rock properties, ground conditions, machine parameters and penetration rate, as these methods rely on past data, their forecasting abilities are limited. The main advantage of this method is that it incorporates the ground conditions and the excavation system as a whole and the prediction estimates are accepted by TBM operators. Barton (1999) gave an equation for estimating the rate of penetration expressed by $Q_{TBM}$ which is a modification of existing Q system (Barton *et al.*, 1974) of rockmass classification for drill and blast tunnels. Many workers have used rockmass rating (RMR) parameter for estimating TBM performance (Bieniawski *et al.*, 2007; Hamidi *et al.*, 2010). Yagiz (2008) added brittleness of intact rock and fracture properties of rockmass as indices into the model. Gong and Zhao (2009) developed a rockmass characteristics model for prediction of TBM penetration rate in granites of Singapore. Performance evaluation of TBM in Deccan Trap rocks was also made along with evaluation of geotechnical properties (Jain, 2014).The RQD analysis has also been associated with the several limitations (Pells *et al.,* 2017). Geotechnical parameters affecting the penetration rate of TBM using neural networks was evaluated based on a case study of Newsoud project in Iran (Hossein *et al.*, 2020). Comparison of various existing empirically based models for estimation of TBM utilization was made using discrete event simulation (Khetwal *et al.*, 2021). Prediction of TBM performance was made using empirical and statistical methods of linear multiple regression and

*(Received : 24 December 2022 ; Revised Form Accepted : 18 April 2023)*
https://doi.org/10.56153/g19088-022-0138-33

nonlinear multiple regression in fresh and weathered granites (Armaghani *et al.*, 2021). Specific rockmass borability index employing regression analysis was developed with incorporation of machine parameters in rockmass characteristics model (Qiuming *et al.*, 2022).

In India, the Government of Andhra Pradesh embarked on AMRP (Alimineti Madhava Reddy Project) with Tunnel1of length 43.93km as one of the components. After bifurcation of state, the project is being implemented by the Government of Telengana. The AMRP project is envisaged to irrigate 1,09, 250 hectares (2.70 lakh acres) in 15 Mandals of Nalgonda District, besides providing drinking water to 516 villages having excessive fluoride in groundwater. Two Robbins TBMs were deployed for boring from Inlet and Outlet ends of Tunnel1with a finished diameter of 9.2M and circular cross section.It is a water transfer tunnel and once completed will be the longest tunnel without intermediate access in the globe (robbinstbm.com). M/s Jaiprakash Associated Ltd is the EPC contractor for this project. This tunnel will transfer water from the left bank of the Krishna River falling in Mahbubnagar District to the Outlet near Mannevaripalli Village, Mahbubnagar District as shown in the layout plan (Fig.1) from where the water will be transferred to the plains of Nalgonda District through a system of canals and Tunnel 2 as part of the AMRP scheme. This long tunnel project provides opportunities for study of rockmass characteristics, geotechnical properties and predictive models of TBM borability in hardrocks such as, archean granites and gneisses and metasedimentary rocks like sandstone, quartzite and quartz arenites.

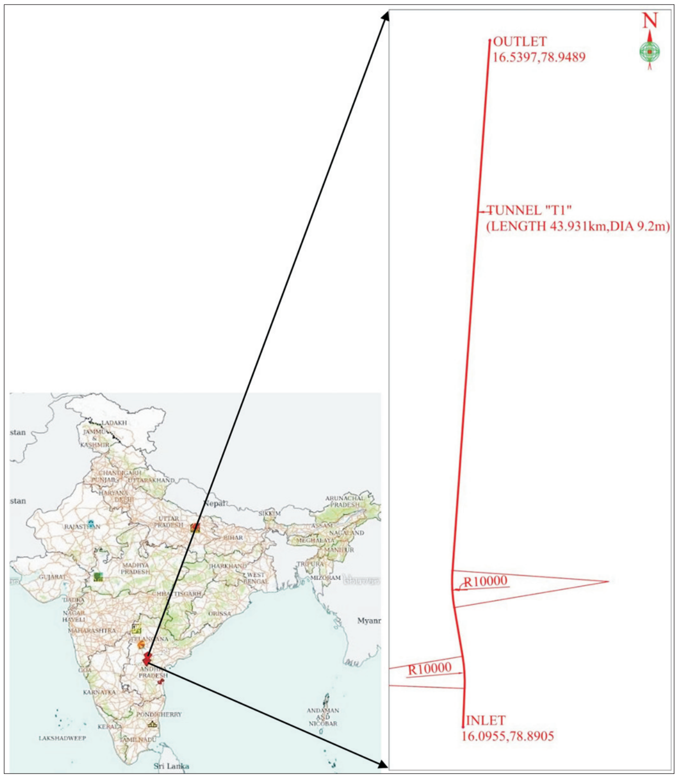

**Fig. 1.** Location Map of Study Area, Telangana State, India

## Scope of the Study

The present study seeks to predict the TBM penetration in two hardrock groups namely, Archean Granites and Gneisses and Meta-sedimentary group comprising of Sandstone, Quartzite and Quartz arenites through the study of Tunnel1 bored in Mahbubnagar District,Telengana state, India.

Sedimentary rocks of weak strength (shale and siltstone) are excluded in the study. The variation of machine parameters like thrust, torque, condition of the machine as well as efficiency of TBM operator is not considered in this work.As the TBMs are double shielded, opportunities to observe the face are limited. Accordingly, construction stage geological mapping and classification of rockmass was carried out (Wilfing, 2016).

## Geology of the Study Area and Tunnel T1

The geological setting comprises of meta-sedimentary rocks namely, Srisailam Quartzites which are interbedded with shale and siltstone and form a part of the Cuddapah Supergroup resting unconformably above the Archean granites and gneisses.This constitutes the tunneling media for Tunnel 1 with Meta-sedimentary group from the Inlet end and Archean granites and gneisses from the Outlet end.

The Srisailam Quartzites constitute the uppermost stage of the Krishna Series in the Cuddapah Super Group and rest unconformably on the Archaean Basement (King, 1872; Sen and Narsimha Rao, 1967). The Cuddapah Basin is one of the Meso-Neoproterozoic sedimentary basins in the east-central part of the Dharwar Craton, crescent in shape, easterly concave, and trends N-S. The arcuate north, south, and western boundary of the Cuddapah Basin marks the profound unconformity (Eparchean Unconformity in early literature) on the basement granites. The arcuate eastern margin is marked by a prominent boundary thrust which is parallel to the Nellore schist belt. A giant basic dyke swarm underlies the basin in the west from Chittoor in the south to Mahbub Nagar in the north (Ramakrishnan and Vaidyanathan, 2008).

Rajurkar and Ramalingaswami (1975) divided the Cuddapah succession into three groups, namely, the lower Cuddapah Group, Nallamalai Group and Kurnool Group. The Srisailam Quartzites are included under the Cumbum slate subgroup of the Nallamalai Group. Meijerink *et al.* (1984) also proposed a three-fold division of the succession and included the Srisailam Formation under the Bairenkonda Subgroup. The Nallamalai Fold Belt (NFB) forms a tectonic boundary with the other rock groups and was excluded from the lithostratigraphic succession (Patranabis-Deb *et al.*, 2012). The NFB is separated from the Cuddapah Basin by the easterly dipping Rudravaram thrust (Das and Chakraborty, 2019). The lithostratigraphic divisions of the Cuddapah System following Nagaraja Rao *et al.* (1987) are adopted in this work (Table 1).

Mandapalli Raju (1989, 2008, 2009) investigated the geotechnical conditions along the tunnel alignment in the SLBC tunnel scheme in the AMRP. Raju (2009) made a geotechnical evaluation of the design parameters for use in the TBMs of the SLBC tunnel with the help of satellite imageries. The geotechnical parameters was mapped and monitored in the construction stage in Tunnel 2 (Ramkrishna and Rao, 2023).

## Methods

The study area falls in Survey of India, topographic sheet numbers 56L/14/SE, 56L/15/NE, 56L/15/SE, 56L/16/NE, 56L/16/SE of Mahbub Nagar district in Telangana state. Tunnel 1 has its Inlet end located at 78$^{o}$53'26” E, 16$^{o}$05'44” N on the left bank

**Table1:** Stratigraphy of Cuddapah Supergroup (*Modified after* Nagaraja Rao *et al.*, 1987)

| Group | Formation | Thickness(m) | Lithology |
|---|---|---|---|
| Kurnool Group | Nandyal Shale | 50±100 | Shale |
| | Koilkuntla Limestone | 15±50 | Limestone |
| | Paniam Quartzite | 10±35 | Quartzite |
| | Owk Shale | 10±15 | Shale (Ocherous) |
| | Narji Limestone | 100±200 | Limestone |
| | Banganapalle Quartzite | 10±50 | Conglomerate, Quartzite |
| | | Unconformity | |
| Srisailam Quartzites | | 300 | Quartzites and Shale |
| | | Unconformity | |
| Nallamalai Group | Cumbum: Phyllite, Slate, quartzite, Dolomite Cumbum (Pullampet) Formation | 2000 | |
| | Bairenkonda (Nagari) Quartzite | 1500± 4000 | Nagari:conglomerate, quartzites, and shales with intrusives |
| | | Angular unconformity | |
| Chitravati Group | Gandikota Quartzite | 300 | |
| | Tadpatri Formation | 4600 | Shale, ash fall tuffs, quartzite, dolomite with intrusives |
| | Pulivendla Quartzite | 1±75 | Conglomerate and quartzite |
| | | Disconformity | |
| Papaghni Group | Vempalli Formation | 1900 | Stromatolitic dolomite, dolomitic mudstone, chert, breccia, and quartzite with basic flows and intrusives |
| | Gulcheru quartzites | 28±210 | Conglomerate, arkose, quartzite and shale |
| | | Nonconformity | |
| | | Archean Gneissic Complex | |

of the Krishna River near Domalapenta Village of Amrabad Mandal upstream of the Srisailam Left Bank Powerhouse while the Outlet end is at 78°56'56" E,16°32'23" N near Mannevaripalli Village, Achampeta Mandal (Fig.1).

As the TBMs are double shielded, opportunities to observe the face are available only during maintenance workand stoppage of machine *viz.* retraction of cutter head, change of disc cutters, seal change, change of the main bearing of TBM. Construction stage geological mapping and collection of rockmass parameters was done as per IS 11315 whenever the opportunity was available. This comprised of rockmass parameters and rockmass quality Q (IS13365, Part2:1992), collected over 126 tunnel section data sets from Outlet end and 66 data sets from Inlet end (Table 2-3). In addition, core and lump samples were recovered from select reaches and were utilized for determining the engineering properties and physical properties. Core samples were recovered using HILTI DD130 core drilling machine.

Physical properties which were determined are bulk density, dry density, porosity, and water content. Engineering Properties determined are unconfined compressive strength (UCS), Tensile strength, and Point Load Strength Index. The results were correlated with penetration rate and statistical models were developed to predict the penetration rate.

## Results and Discussion

### *Variation of TBM Penetration Rate with RQD*

Rock Quality Designation (RQD) was determined by indirect methods based on degree of jointing (IS11315, Part 11). The RQD values determined for Tunnel 1 for the Meta-sedimentary rock group (Table 2) and the Archean rocks (Table 3).

Figure 2 shows the variation of TBM penetration rate with rock quality designation (RQD) in the Archean rocks. It can be observed that as RQD increases the penetration rate decreases exponentially as

$$PR = 3.7778e^{-0.014RQD} \quad (1)$$

and $R^2 = 0.8101$

Figure 3 shows the variation of TBM penetration rate with RQD in the Meta-sedimentary rock group. It can be observed that penetration rate varies with RQD as a polynomial function of second order with

$$PR= -0.0015RQD^2 + 0.1612RQD - 1.9264 \quad (2)$$

and $R^2 = 0.9732$.

Second order equation gives a better degree of fit when compared to first order equation. $R^2$ values of 0.81 and 0.97 show a good correlation between TBM penetration rate and RQD.

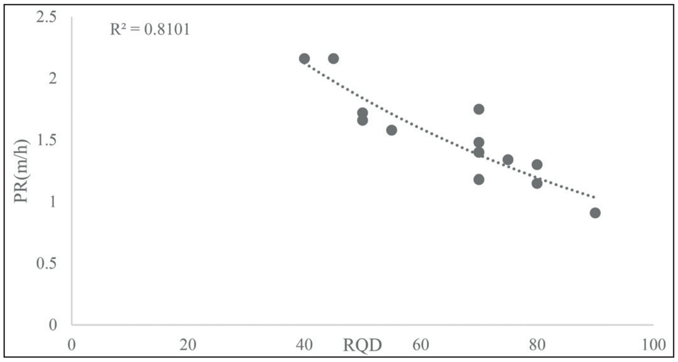

**Fig. 2.** Variation of Penetration Rate (PR) with RQD in Archean Rocks

**Table 2:** Rockmass Parameters of Tunnel - 1 from Inlet end

| CHAINAGE (M) | RQD | $J_N$ | RQD / JN | $J_R$ | $J_A$ | $J_R/J_A$ | $J_W$ | SRF | $J_W$/ SRF | Q-Value | Jv | Rockmass Category | Rockmass Class |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 42 | 37.5 | 12 | 3.1 | 1 | 1 | 1 | 1 | 1 | 1 | 3.1 | 23.5 | IV | Poor |
| 45 | 47.5 | 10.5 | 4.5 | 1 | 1 | 1 | 1 | 1 | 1 | 4.5 | 20.5 | III | Fair |
| 53 | 50 | 9 | 5.6 | 1 | 1 | 1 | 1 | 1 | 1 | 5.6 | 19.7 | III | Fair |
| 68 | 50 | 10.5 | 4.8 | 1 | 1 | 1 | 1 | 1 | 1 | 4.8 | 19.7 | III | Fair |
| 88 | 47.5 | 12 | 4.0 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 5.9 | 20.5 | III | Fair |
| 129 | 50 | 9 | 5.6 | 1.5 | 1 | 1.5 | 0.66 | 1 | 0.66 | 5.5 | 19.7 | III | Fair |
| 198 | 52.5 | 9 | 5.8 | 1.5 | 1 | 1.5 | 0.66 | 1 | 0.66 | 5.8 | 18.9 | III | Fair |
| 207 | 52.5 | 12 | 4.4 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 6.6 | 18.9 | III | Fair |
| 283 | 52.5 | 9 | 5.8 | 1 | 1 | 1 | 1 | 1 | 1 | 5.8 | 18.9 | III | Fair |
| 336 | 52.5 | 9 | 5.8 | 1 | 1 | 1 | 1 | 1 | 1 | 5.8 | 18.9 | III | Fair |
| 419 | 57.5 | 9 | 6.4 | 1 | 1 | 1 | 1 | 1 | 1 | 6.4 | 17.4 | III | Fair |
| 529 | 57.5 | 9 | 6.4 | 1 | 1 | 1 | 1 | 1 | 1 | 6.4 | 17.4 | III | Fair |
| 590 | 57.5 | 9 | 6.4 | 1 | 1 | 1 | 1 | 1 | 1 | 6.4 | 17.4 | III | Fair |
| 669 | 60 | 9 | 6.7 | 1 | 1 | 1 | 1 | 1 | 1 | 6.7 | 16.7 | III | Fair |
| 698 | 60 | 9 | 6.7 | 1 | 1 | 1 | 1 | 1 | 1 | 6.7 | 16.7 | III | Fair |
| 744 | 60 | 9 | 6.7 | 1 | 1 | 1 | 1 | 1 | 1 | 6.7 | 16.7 | III | Fair |
| 843 | 55 | 12 | 4.6 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 6.9 | 18.2 | III | Fair |
| 1107 | 62.5 | 12 | 5.2 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 7.8 | 15.9 | III | Fair |
| 1178 | 52.5 | 12 | 4.4 | 1.5 | 1 | 1.5 | 1 | 1.25 | 0.8 | 5.3 | 18.9 | III | Fair |
| 1259 | 62.5 | 9 | 6.9 | 1 | 1 | 1 | 1 | 1 | 1 | 6.9 | 15.9 | III | Fair |
| 1560 | 65 | 9 | 7.2 | 1 | 1 | 1 | 1 | 1 | 1 | 7.2 | 15.2 | III | Fair |
| 1845 | 60 | 15 | 4.0 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 6.0 | 16.7 | III | Fair |
| 2030 | 60 | 12 | 5.0 | 1 | 1 | 1 | 1 | 1 | 1 | 5.0 | 16.7 | III | Fair |
| 2165 | 50 | 12 | 4.2 | 1 | 1 | 1 | 1 | 1 | 1 | 4.2 | 19.7 | III | Fair |
| 2295 | 55 | 9 | 6.1 | 1 | 1 | 1 | 1 | 1 | 1 | 6.1 | 18.2 | III | Fair |
| 2365 | 47.5 | 12 | 3.96 | 1 | 1 | 1 | 1 | 1 | 1 | 3.96 | 20.5 | IV | Poor |
| 2511 | 62.5 | 9 | 6.94 | 1.5 | 1 | 1.5 | 1 | 2.5 | 0.4 | 4.17 | 15.9 | III | Fair |
| 2614 | 60 | 9 | 6.67 | 1 | 1 | 1 | 1 | 1 | 1 | 6.67 | 16.7 | III | Fair |
| 2740 | 60 | 6 | 10.00 | 1 | 1 | 1 | 1 | 1 | 1 | 10.00 | 16.7 | III | Fair |
| 2833 | 62.5 | 12 | 5.21 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 7.81 | 15.9 | III | Fair |
| 2944 | 60 | 9 | 6.67 | 1.5 | 1 | 1.5 | 0.66 | 1 | 0.66 | 6.60 | 16.7 | III | Fair |
| 3046 | 47.5 | 12 | 3.96 | 1.5 | 1 | 1.5 | 1 | 1.25 | 0.8 | 4.75 | 20.5 | III | Fair |
| 3254 | 57.5 | 6 | 9.6 | 1 | 1 | 1 | 1 | 1 | 1 | 9.6 | 17.4 | III | Fair |
| 3391 | 47.5 | 12 | 4.0 | 1 | 1 | 1 | 1 | 1.25 | 0.8 | 3.2 | 20.5 | IV | Poor |
| 3907 | 67.5 | 10.5 | 6.4 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 9.6 | 14.4 | III | Fair |
| 4056 | 60 | 12 | 5.0 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 7.5 | 16.7 | III | Fair |
| 4156 | 62.5 | 6 | 10.4 | 1 | 1 | 1 | 1 | 1 | 1 | 10.4 | 15.9 | II | Good |
| 4271 | 67.5 | 6 | 11.3 | 1 | 1 | 1 | 1 | 1 | 1 | 11.3 | 14.4 | II | Good |
| 4402 | 57.5 | 9 | 6.4 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 9.6 | 17.4 | III | Fair |
| 4601 | 60 | 9 | 6.7 | 1 | 1 | 1 | 1 | 1 | 1 | 6.7 | 16.7 | III | Fair |
| 4828 | 65 | 9 | 7.2 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 10.8 | 15.2 | II | Good |
| 4924 | 60 | 10.5 | 5.7 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 8.6 | 16.7 | III | Fair |
| 5020 | 60 | 10.5 | 5.7 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 8.6 | 16.7 | III | Fair |
| 5206 | 57.5 | 9 | 6.4 | 1 | 1 | 1 | 1 | 1 | 1 | 6.4 | 17.4 | III | Fair |
| 5311 | 55 | 10.5 | 5.2 | 1 | 1 | 1 | 1 | 1 | 1 | 5.2 | 18.2 | III | Fair |
| 5389 | 52.5 | 9 | 5.8 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 8.8 | 18.9 | III | Fair |
| 5700 | 60 | 9 | 6.7 | 1 | 1 | 1 | 1 | 1 | 1 | 6.7 | 16.7 | III | Fair |
| 6064 | 52.5 | 9 | 5.8 | 1 | 1 | 1 | 1 | 1 | 1 | 5.8 | 18.9 | III | Fair |
| 6184 | 52.5 | 10.5 | 5.0 | 1 | 1 | 1 | 1 | 1 | 1 | 5.0 | 18.9 | III | Fair |
| 6302 | 60 | 9 | 6.7 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 10.0 | 16.7 | III | Fair |
| 6415 | 62.5 | 9 | 6.9 | 1 | 1 | 1 | 1 | 1 | 1 | 6.9 | 15.9 | III | Fair |
| 6467 | 62.5 | 6 | 10.4 | 1 | 1 | 1 | 1 | 1 | 1 | 10.4 | 15.9 | II | Good |
| 6881 | 70 | 9 | 7.8 | 1 | 1 | 1 | 1 | 1 | 1 | 7.8 | 13.6 | III | Fair |
| 7004 | 70 | 10.5 | 6.7 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 10.0 | 13.6 | II | Good |
| 7127 | 72.5 | 9 | 8.1 | 1 | 1 | 1 | 1 | 1 | 1 | 8.1 | 12.9 | III | Fair |
| 7302 | 77.5 | 9 | 8.6 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 12.9 | 11.4 | II | Good |
| 7406 | 77.5 | 6 | 12.9 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 19.4 | 11.4 | II | Good |
| 7468 | 85 | 6 | 14.2 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 21.3 | 9.1 | II | Good |
| 7731 | 65 | 10.5 | 6.2 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 9.3 | 15.2 | III | Fair |
| 7776 | 52.5 | 12 | 4.4 | 1.5 | 1 | 1.5 | 1 | 2.5 | 0.4 | 2.6 | 18.9 | IV | Poor |
| 8200 | 62.5 | 6 | 10.4 | 1 | 1 | 1 | 1 | 1 | 1 | 10.4 | 15.9 | II | Good |
| 8560 | 60 | 12 | 5.0 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 7.5 | 16.7 | III | Fair |
| 8698 | 65 | 9 | 7.2 | 1.5 | 1 | 1.5 | 1 | 1 | 1 | 10.8 | 15.2 | II | Good |
| 8768 | 65 | 6 | 10.8 | 1 | 1 | 1 | 1 | 1 | 1 | 10.8 | 15.2 | II | Good |
| 8800 | 60 | 6 | 10.0 | 1 | 1 | 1 | 1 | 2.5 | 0.4 | 4.0 | 16.7 | III | Fair |
| 8837 | 67.5 | 9 | 7.5 | 1 | 1 | 1 | 0.66 | 1 | 0.66 | 5.0 | 14.4 | III | Fair |

**Table 3:** Rockmass Parameters of Tunnel - 1 Outlet end

| Reduced Distance, RD (M) | Chainage (M) | RQD | $J_N$ | RQD / $J_N$ | $J_R$ | $J_A$ | JR/ $J_A$ | $J_W$ | SRF | $J_W$ / SRF | Q-Value | JV | Rockmass category | Rockmass Class |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 43931 | 80 | 18 | 4.4 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 6.7 | 10.6 | III | Fair |
| 2.5 | 43928.5 | 80 | 18 | 4.4 | 2 | 1 | 1.5 | 1 | 1.3 | 0.8 | 5.3 | 10.6 | III | Fair |
| 10 | 43921 | 80 | 9 | 8.9 | 2 | 1 | 1.5 | 0.7 | 1 | 0.7 | 8.8 | 10.6 | III | Fair |
| 14 | 43917 | 85 | 9 | 9.4 | 2 | 1 | 1 | 1 | 1.5 | 0.7 | 9.4 | 9.1 | III | Fair |
| 19.5 | 43911.5 | 85 | 12 | 7.1 | 2 | 1 | 1 | 1 | 2.5 | 0.4 | 4.3 | 9.1 | III | Fair |
| 28.5 | 43902.5 | 90 | 9 | 10.0 | 2 | 1 | 1 | 1 | 1 | 1.0 | 12.0 | 7.6 | II | Good |
| 136.5 | 43794.5 | 95 | 3 | 31.7 | 2 | 1 | 1.5 | 0.7 | 1 | 0.7 | 31.4 | 6.1 | II | Good |
| 524 | 43407 | 70 | 6 | 11.7 | 1 | 1 | 1 | 1 | 1.5 | 0.7 | 7.8 | 13.6 | III | Fair |
| 1125 | 42806 | 87.5 | 6 | 14.6 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 21.9 | 8.3 | II | Good |
| 1363 | 42568 | 90 | 3 | 30.0 | 1 | 1 | 1 | 1 | 1 | 1.0 | 30.0 | 7.6 | II | Good |
| 1697 | 42234 | 90 | 3 | 30.0 | 1 | 1 | 1 | 1 | 1 | 1.0 | 30.0 | 7.6 | II | Good |
| 1874 | 42057 | 95 | 4 | 23.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 35.6 | 6.1 | II | Good |
| 2000 | 41931 | 87.5 | 4 | 21.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 32.8 | 8.3 | II | Good |
| 2092.5 | 41838.5 | 85 | 4 | 21.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 31.9 | 9.1 | II | Good |
| 2168.9 | 41762.1 | 77.5 | 4 | 19.4 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 29.1 | 11.4 | II | Good |
| 2262 | 41669 | 87.5 | 4 | 21.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 32.8 | 8.3 | II | Good |
| 2740 | 41191 | 85 | 6 | 14.2 | 1 | 1 | 1 | 1 | 1 | 1.0 | 14.2 | 9.1 | II | Good |
| 2820 | 41111 | 87.5 | 3 | 29.2 | 1 | 1 | 1 | 1 | 1 | 1.0 | 29.2 | 8.3 | II | Good |
| 2910 | 41021 | 77.5 | 9 | 8.6 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 12.9 | 11.4 | II | Good |
| 3021.9 | 40909.1 | 82.5 | 4 | 20.6 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 30.9 | 9.8 | II | Good |
| 3144.2 | 40786.8 | 77.5 | 4 | 19.4 | 1 | 1 | 1 | 1 | 1 | 1.0 | 19.4 | 11.4 | II | Good |
| 3324 | 40607 | 72.5 | 9 | 8.1 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 12.1 | 12.9 | II | Good |
| 3568 | 40363 | 87.5 | 4 | 21.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 32.8 | 8.3 | II | Good |
| 3682 | 40249 | 77.5 | 6 | 12.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 19.4 | 11.4 | II | Good |
| 3835 | 40096 | 82.5 | 4 | 20.6 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 30.9 | 9.8 | II | Good |
| 3925.2 | 40005.8 | 80 | 4 | 20.0 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 30.0 | 10.6 | II | Good |
| 3941.5 | 39989.5 | 77.5 | 9 | 8.6 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 12.9 | 11.4 | II | Good |
| 4098.6 | 39832.4 | 72.5 | 11 | 6.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.4 | 12.9 | II | Good |
| 4410.6 | 39520.4 | 50 | 15 | 3.3 | 2 | 1 | 1.5 | 0.7 | 1 | 0.7 | 3.3 | 19.7 | IV | Poor |
| 4539.3 | 39391.7 | 57.5 | 11 | 5.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 8.2 | 17.4 | III | Fair |
| 4575.6 | 39355.4 | 77.5 | 11 | 7.4 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 11.1 | 11.4 | II | Good |
| 4624.4 | 39306.6 | 75 | 6 | 12.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.8 | 12.1 | II | Good |
| 4740.2 | 39190.8 | 72.5 | 4 | 18.1 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 27.2 | 12.9 | II | Good |
| 5042.8 | 38888.2 | 67.5 | 6 | 11.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.9 | 14.4 | II | Good |
| 5103.5 | 38827.5 | 65 | 6 | 10.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.3 | 15.2 | II | Good |
| 5140.3 | 38790.7 | 65 | 6 | 10.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.3 | 15.2 | II | Good |
| 5230 | 38701 | 67.5 | 4 | 16.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 25.3 | 14.4 | II | Good |
| 5293.5 | 38637.5 | 70 | 4 | 17.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 26.3 | 13.6 | II | Good |
| 5314.8 | 38616.2 | 75 | 4 | 18.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 28.1 | 12.1 | II | Good |
| 5372.5 | 38558.5 | 60 | 6 | 10.0 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 15.0 | 16.7 | II | Good |
| 5404 | 38527 | 72.5 | 6 | 12.1 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.1 | 12.9 | II | Good |
| 5455.6 | 38475.4 | 80 | 6 | 13.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 20.0 | 10.6 | II | Good |
| 5487.3 | 38443.7 | 80 | 6 | 13.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 20.0 | 10.6 | II | Good |
| 5566 | 38365 | 65 | 6 | 10.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.3 | 15.2 | II | Good |
| 5666 | 38265 | 67.5 | 6 | 11.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.9 | 14.4 | II | Good |
| 5711.8 | 38219.2 | 77.5 | 6 | 12.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 19.4 | 11.4 | II | Good |
| 5736.4 | 38194.6 | 75 | 6 | 12.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.8 | 12.1 | II | Good |
| 5766 | 38165 | 75 | 6 | 12.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.8 | 12.1 | II | Good |
| 5811 | 38120 | 77.5 | 6 | 12.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 19.4 | 11.4 | II | Good |
| 5871.7 | 38059.3 | 80 | 4 | 20.0 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 30.0 | 10.6 | II | Good |
| 5924.6 | 38006.4 | 67.5 | 9 | 7.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 11.3 | 14.4 | II | Good |
| 5977.8 | 37953.2 | 72.5 | 6 | 12.1 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.1 | 12.9 | II | Good |
| 6031.6 | 37899.4 | 57.5 | 12 | 4.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 7.2 | 17.4 | III | Fair |
| 6072.6 | 37858.4 | 62.5 | 9 | 6.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.4 | 15.9 | II | Good |
| 6103.35 | 37827.65 | 57.5 | 9 | 6.4 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 9.6 | 17.4 | III | Fair |
| 6149.65 | 37781.35 | 60 | 9 | 6.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.0 | 16.7 | II | Good |
| 6189 | 37742 | 60 | 9 | 6.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.0 | 16.7 | II | Good |
| 6214 | 37717 | 50 | 12 | 4.2 | 2 | 1 | 1.5 | 1 | 1.3 | 0.8 | 5.0 | 19.7 | III | Fair |
| 6227 | 37704 | 60 | 9 | 6.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.0 | 16.7 | II | Good |
| 6383.1 | 37547.9 | 65 | 9 | 7.2 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.8 | 15.2 | II | Good |
| 6430 | 37501 | 50 | 12 | 4.2 | 2 | 1 | 1.5 | 1 | 1.3 | 0.8 | 5.0 | 19.7 | III | Fair |
| 6609.6 | 37321.4 | 67.5 | 6 | 11.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.9 | 14.4 | II | Good |
| 6672 | 37259 | 67.5 | 9 | 7.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 11.3 | 14.4 | II | Good |
| 6873.3 | 37057.7 | 60 | 6 | 10.0 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 15.0 | 16.7 | II | Good |
| 7024 | 36907 | 67.5 | 6 | 11.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.9 | 14.4 | II | Good |
| 7146 | 36785 | 62.5 | 12 | 5.2 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 7.8 | 15.9 | III | Fair |
| 7220.2 | 36710.8 | 57.5 | 12 | 4.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 7.2 | 17.4 | III | Fair |
| 7287 | 36644 | 47.5 | 12 | 4.0 | 2 | 1 | 1.5 | 0.7 | 1 | 0.7 | 3.9 | 20.5 | IV | Poor |
| 7293 | 36638 | 40 | 12 | 3.3 | 2 | 1 | 1.5 | 0.7 | 1 | 0.7 | 3.3 | 22.7 | IV | Poor |
| 7320 | 36611 | 40 | 15 | 2.7 | 2 | 1 | 1.5 | 1 | 1.3 | 0.8 | 3.2 | 22.7 | IV | Poor |
| 7332.96 | 36598.04 | 47.5 | 12 | 4.0 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 5.9 | 20.5 | III | Fair |
| 7397 | 36534 | 45 | 11 | 4.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 6.4 | 21.2 | III | Fair |

*Contd ...*

*Table 3: Contd ...*

| Reduced Distance, RD (M) | Chainage (M) | RQD | $J_N$ | RQD / $J_N$ | $J_R$ | $J_A$ | JR/ $J_A$ | $J_W$ | SRF | $J_W$ / SRF | Q-Value | Jv | Rockmass category | Rockmass Class |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7456 | 36475 | 55 | 11 | 5.2 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 7.9 | 18.2 | III | Fair |
| 7481 | 36450 | 57.5 | 9 | 6.4 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 9.6 | 17.4 | III | Fair |
| 7505.7 | 36425.3 | 52.5 | 9 | 5.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 8.8 | 18.9 | III | Fair |
| 7524.8 | 36406.2 | 60 | 9 | 6.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.0 | 16.7 | II | Good |
| 7635 | 36296 | 65 | 9 | 7.2 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.8 | 15.2 | II | Good |
| 7723 | 36208 | 57.5 | 9 | 6.4 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 9.6 | 17.4 | III | Fair |
| 7747.3 | 36183.7 | 67.5 | 9 | 7.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 11.3 | 14.4 | II | Good |
| 7832 | 36099 | 67.5 | 6 | 11.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.9 | 14.4 | II | Good |
| 7852.4 | 36078.6 | 70 | 6 | 11.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 17.5 | 13.6 | II | Good |
| 7922 | 36009 | 67.5 | 6 | 11.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.9 | 14.4 | II | Good |
| 7978 | 35953 | 70 | 6 | 11.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 17.5 | 13.6 | II | Good |
| 8056 | 35875 | 75 | 4 | 18.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 28.1 | 12.1 | II | Good |
| 8094.6 | 35836.4 | 75 | 4 | 18.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 28.1 | 12.1 | II | Good |
| 8107.2 | 35823.8 | 70 | 6 | 11.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 17.5 | 13.6 | II | Good |
| 8190 | 35741 | 67.5 | 6 | 11.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.9 | 14.4 | II | Good |
| 8235.3 | 35695.7 | 65 | 6 | 10.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.3 | 15.2 | II | Good |
| 8275 | 35656 | 65 | 6 | 10.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.3 | 15.2 | II | Good |
| 8289.85 | 35641.15 | 67.5 | 6 | 11.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.9 | 14.4 | II | Good |
| 8317 | 35614 | 77.5 | 4 | 19.4 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 29.1 | 11.4 | II | Good |
| 8363 | 35568 | 77.5 | 6 | 12.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 19.4 | 11.4 | II | Good |
| 8440.2 | 35490.8 | 67.5 | 6 | 11.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 16.9 | 14.4 | II | Good |
| 8502 | 35429 | 62.5 | 12 | 5.2 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 7.8 | 15.9 | III | Fair |
| 8676 | 35255 | 80 | 3 | 26.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 40.0 | 10.6 | I | Very Good |
| 8718.2 | 35212.8 | 72.5 | 6 | 12.1 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.1 | 12.9 | II | Good |
| 8781 | 35150 | 70 | 6 | 11.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 17.5 | 13.6 | II | Good |
| 8818 | 35113 | 70 | 11 | 6.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.0 | 13.6 | III | Fair |
| 8861.8 | 35069.2 | 70 | 6 | 11.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 17.5 | 13.6 | II | Good |
| 8915 | 35016 | 70 | 6 | 11.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 17.5 | 13.6 | II | Good |
| 8942.3 | 34988.7 | 72.5 | 6 | 12.1 | 1 | 1 | 1 | 1 | 1 | 1.0 | 12.1 | 12.9 | II | Good |
| 8981.2 | 34949.8 | 72.5 | 6 | 12.1 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.1 | 12.9 | II | Good |
| 9022.79 | 34908.21 | 67.5 | 12 | 5.6 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 8.4 | 14.4 | III | Fair |
| 9058.13 | 34872.87 | 65 | 9 | 7.2 | 2 | 1 | 1.5 | 1 | 1.3 | 0.8 | 8.7 | 15.2 | III | Fair |
| 9087.3 | 34843.7 | 47.5 | 9 | 5.3 | 2 | 1 | 1.5 | 1 | 1.3 | 0.8 | 6.3 | 20.5 | III | Fair |
| 9122 | 34809 | 52.5 | 12 | 4.4 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 6.6 | 18.9 | III | Fair |
| 9154.2 | 34776.8 | 67.5 | 9 | 7.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 11.3 | 14.4 | II | Good |
| 9200 | 34731 | 67.5 | 9 | 7.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 11.3 | 14.4 | II | Good |
| 9224.6 | 34706.4 | 72.5 | 6 | 12.1 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.1 | 12.9 | II | Good |
| 9268.5 | 34662.5 | 72.5 | 6 | 12.1 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.1 | 12.9 | II | Good |
| 9287 | 34644 | 67.5 | 9 | 7.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 11.3 | 14.4 | II | Good |
| 9298 | 34633 | 72.5 | 6 | 12.1 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.1 | 12.9 | II | Good |
| 9367 | 34564 | 67.5 | 9 | 7.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 11.3 | 14.4 | II | Good |
| 9421.5 | 34509.5 | 80 | 6 | 13.3 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 20.0 | 10.6 | II | Good |
| 9473.9 | 34457.1 | 70 | 9 | 7.8 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 11.7 | 13.6 | II | Good |
| 9523.3 | 34407.7 | 62.5 | 9 | 6.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.4 | 15.9 | II | Good |
| 9570.15 | 34360.85 | 52.5 | 12 | 4.4 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 6.6 | 18.9 | III | Fair |
| 9653 | 34278 | 62.5 | 9 | 6.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.4 | 15.9 | II | Good |
| 9682.1 | 34248.9 | 62.5 | 9 | 6.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.4 | 15.9 | II | Good |
| 9724 | 34207 | 62.5 | 9 | 6.9 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 10.4 | 15.9 | II | Good |
| 9875 | 34056 | 57.5 | 9 | 6.4 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 9.6 | 17.4 | III | Fair |
| 9942.4 | 33988.6 | 70 | 6 | 11.7 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 17.5 | 13.6 | II | Good |
| 9984.5 | 33946.5 | 90 | 4 | 22.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 33.8 | 7.6 | II | Good |
| 10009 | 33922 | 75 | 6 | 12.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.8 | 12.1 | II | Good |
| 10036.6 | 33894.4 | 72.5 | 6 | 12.1 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.1 | 12.9 | II | Good |
| 10046.46 | 33884.54 | 75 | 6 | 12.5 | 2 | 1 | 1.5 | 1 | 1 | 1.0 | 18.8 | 12.1 | II | Good |

### ***Variation of TBM Penetration Rate with Unconfined Compressive Strength (UCS)***

Unconfined Compressive strength (UCS) is one of the most common parameters of describing the intact rock strength.TBM penetration is possible only when the applied forces exceed the UCS of the rockmass (Roxborough and Phillips, 1975). UCS is also one of the factors influencing rockabrasivity (Plinninger, 2010).

Figure 4 shows the variation of penetration rate with unconfined compressive strength (UCS) in the Archaean formation from the Outlet end performed on intact rock samples. As stress-strain behaviour of rock is nonlinear and because of medium strong (R3) to very strong (R5) rock (ISRM1981) encountered in tunnelling there is considerable scatter of data. A linear fit for PR with UCS gives very low $R^{2.}$ Accordingly, to obtain a better fit, a polynomial function of order three is given in equation (3).

$$PR = -3E\text{-}11UCS^3 + 6E\text{-}08UCS^2 + 0.0001UCS + 1.3326 \quad (3)$$

with $R^2$ of 0.0341.-

Figure 5 shows the variation of penetration rate with UCS in the metasedimentary formation from the Inlet end. The penetration rate decreases with UCS as a polynomial function of order two given by

$$PR= -1E\text{-}05UCS^2 + 0.0091UCS + 0.9413 \quad (4)$$

with a $R^2$ value of 0.69 showing good correlation.

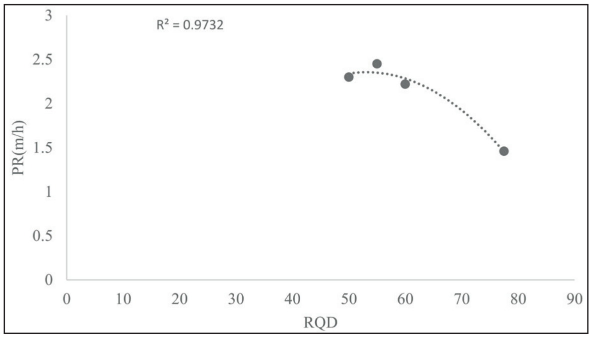

**Fig. 3.** Variation of Penetration Rate (PR) with RQD in Meta-sedimentary Rocks

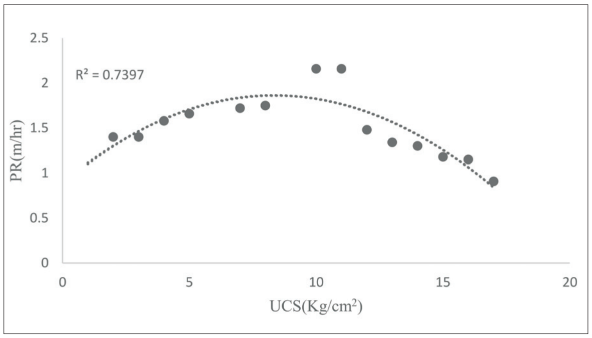

**Fig. 4.** Variation of Penetration Rate with Unconfined Compressive Strength (UCS) in Archean Rocks

It can be inferred that TBM penetration rate shows a good correlation with UCS in Meta Sedimentary rock group and poor correlation in the medium to high strength crystalline rocks of the Archean group. The reason for poor correlation in the granites/gneisses may be due to the wear of cutter discs when boring in rockmass of variable grades fromR3 to R5 as compared to the metasedimentary rocks where only medium strong (R3) to strong rock (R4) was encountered.

### *Variation of Porosity with Unconfined Compressive Strength (UCS)*

Mikhail (2020) studied the effect of porosity on the unconfined compressive strength of Kuznetsk Basin sandstones in Siberia, Russia. Figure 6 shows the variation of porosity with unconfined compressive strength (UCS) in the metasedimentary. It can be seen that UCS decreases as a second-order polynomial function with an increase in porosity in the metasedimentary rocks, as shown in Figure 6 and given by equation (5) with $R^2 = 0.5765$.

$$UCS=193.4POROSITY^{-0.656} \quad (5)$$

### *Variation of TBM Penetration Rate with Volumetric Joint Count (Jv) and Tensile Strength*

During the TBM boring process, presence of joints will have a favourable effect on the penetration rate up to a certain spacing (Bruland, 1998; Wilfing, 2016).

Figure 7a-b shows the variation of penetration rate with volumetric joint count (Jv) in the Archeans and Meta-sedimentary. Jv is obtained from RQD from the formula RQD =115-3.3Jv when rock cores are not available (IS13365, Part1:1998). It can be observed that penetration rate increases exponentially with (Jv) in the archean sand meta-sedimentary rock groups with $R^2$ = 0.8167and 0.8275, respectively and shown by equations (6) and (7).

$$PR = 0.7047e^{0.0491Jv} \quad (6)$$

$$PR = 0.7416e^{0.0634Jv} \quad (7)$$

Figure 8a-b show the variation of Jv with tensile strength determined in the laboratory for 17 core samples on intact rock. It can be observed that in Archean Group, Jv varies as a polynomial function of the tensile strength of the rock with $R^2$ of 0.0562 showing poor correlation.

$$\text{Tensile Strength} = -0.1954Jv^2 + 5.1371Jv + 57.234 \quad (8)$$

Figure 8b shows the variation of Jv with tensile strength in the meta-sedimentary group. The Jv shows a better correlation with Tensile strength in the metasedimentary when compared to Archean, and it varies as a second order polynomial with $R^2$ of 0.2349

$$\text{Tensile strength} = -7.2963Jv^2 + 266.47Jv - 2342 \quad (9)$$

### *Variation of TBM Penetration Rate with Rockmass Class*

Rockmass characterisation with Q-system(IS13365, Part2: 1992) provides a field method of classifying the rockmass into five classes from Class I (Very Good Rock) to V(Very Poor rock). RQD/Jn is a crude measure of the block size where Jn is the Joint set number obtained from face logging of excavation.

Figure 9 shows the variation of rockmass class with TBM penetration rate in the Archean Group. It is evident that higher

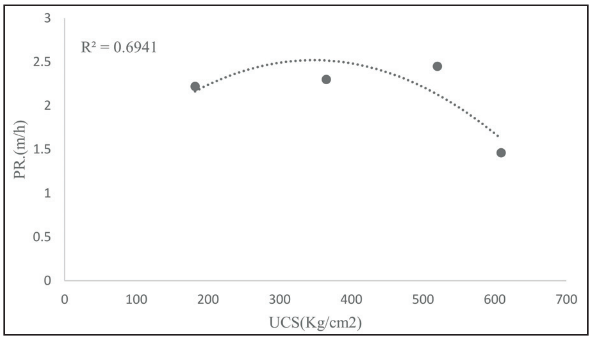

**Fig. 5.** Variation of Penetration Rate with Unconfined Compressive Strength (UCS) in Meta-sedimentary Rocks

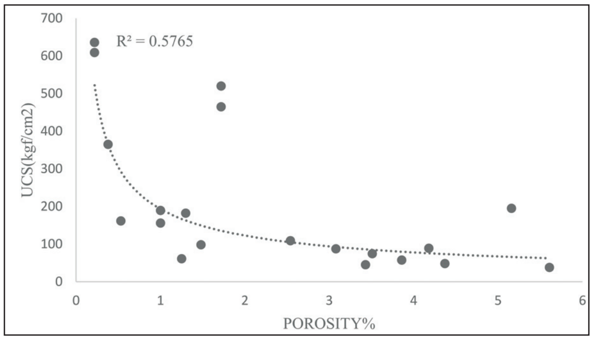

**Fig. 6.** Variation of Porosity with Unconfined Compressive Strength (UCS) in Meta-sedimentary Rocks

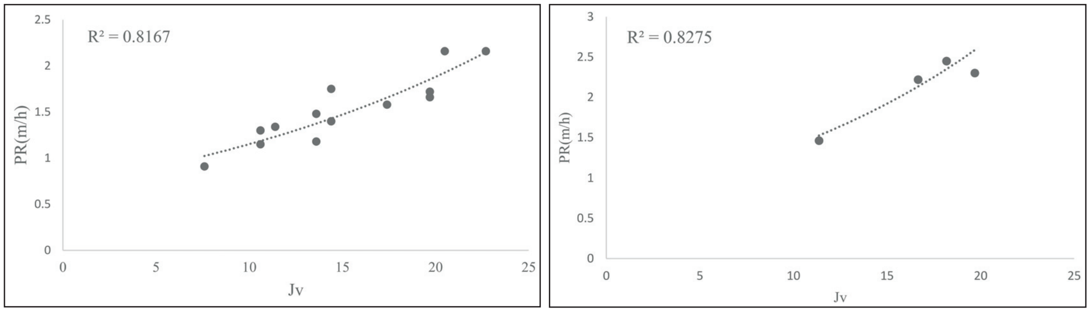

**Fig. 7.** Variation of Penetration Rate with (a) $J_v$ in Archean Rocks (b) $J_v$ in Meta-sedimentary Rocks

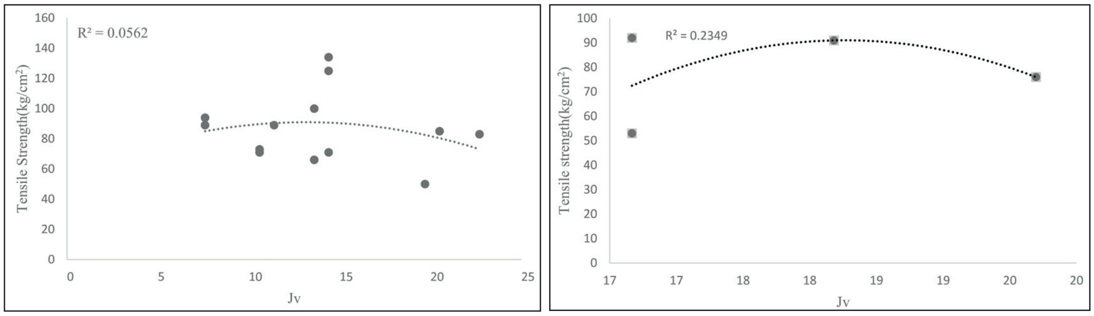

**Fig. 8.**Variation of Tensile Strength with (a) $J_v$ in Archeans Rocks (b) $J_v$ in Meta-sedimentary Rocks

penetration rates are achieved in Class III and ClassIV rock when compared with Class I and II. Figure 10 shows the variation of rockmass class with penetration rate in the meta-sedimentary formation. It can be observed that higher penetration rate was obtained in Class III rock when compared to Class II rock.

## Conclusions

TBM penetration rate in hard rocks comprising of granites, granite gneisses, quartzites, sandstones and quartz arenites of Archean and meta-sedimentary rock groups was investigated. It is inferred that penetration rate shows a good correlation with RQD for both Archean and meta-sedimentary rock groups as well as with UCS in the Meta Sedimentary rock group but poorly in the medium to very strong crystalline rocks of the Archean Group. Penetration rate increases exponentially with joint volume in both the rock groups. Volumetric joint count (Jv) does not show any significant correlation with Tensile strength in both the rock groups with relatively better correlation in the Meta-sedimentary group. Porosity increases exponentially with decrease in UCS in the meta-sedimentary group.

## Authors' Contributions

**RD**: Investigation, Conceptualisation, Methodology, Writing-Original Draft, Formal Analysis. **RRN**: Supervision, Reviewing and Editing.

## Conflict of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgements

The first author acknowledges the support received from M/s Jaiprakash Associates Ltd (Jaypee Group) India in all stages of work and permission to utilize the data (Letter No. JAL/SSTP/03/21/10047A dated 28.12.2021). Support received from the Field staff of M/s Jaiprakash Associated Ltd. is also gratefully acknowledged. Special thanks are also due to the Head of Department, Department of Applied Geology, University of Madras, Guindy Campus, Chennai, and the President of Dr. M. G. R. Educational and Research Institute, Chennai, for their encouragement and support.

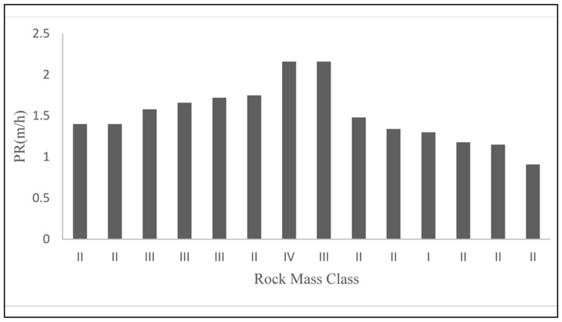

**Fig. 9.** PR with Rock Mass Class in Archean Rocks

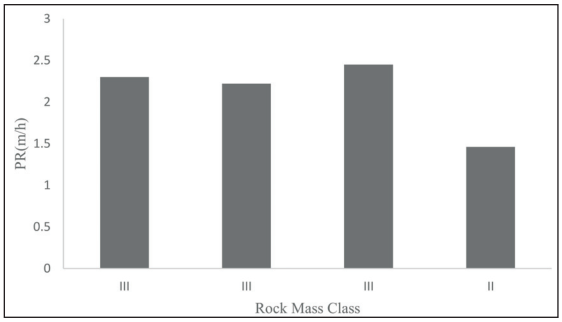

**Fig. 10.** PR with Rock Mass Class in Meta-sedimentary Rocks

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