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Data analysis for the assessment of roadheader performance in carbonate rocks

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Abstract

Utilizing roadheaders (RH) and estimating their cutting rate in rock excavation are crucial for effective scheduling in mechanized mining and civil construction projects. Roadheaders are widely used for tunnelling in civil engineering and are commonly applied in coal mining for production and for driving drifts to access ore bodies. They are typically suitable for excavating weak to medium-strength rocks (20–160 MPa); however, with advances in technology, they can now be used in non-abrasive rocks with uniaxial compressive strength (UCS) of up to 200 MPa. In this study, a 4 km-long tunnel excavated in China using an axial roadheader is examined. The analysis considers intact rock properties (UCS and Brazilian tensile strength), rock mass properties (frequency and features of discontinuities), and machine specifications (e.g., cutting power) to evaluate RH performance. A dataset comprising 1,755 data points, including field and laboratory measurements as well as machine parameters, was compiled and analyzed. The relationships between the input variables and the instantaneous cutting rate (ICR) were then investigated, and empirical models are proposed for practical applications. The results indicate that ICR can be predicted more accurately when intact rock properties, rock mass characteristics, and machine parameters are considered together, thereby improving project scheduling in both mining and civil engineering applications.

Keywords

Brazilian Tensile Strength, RH-Power, Roadheader, Rock Quality Designation, Uniaxial Compressive Strength.

1 Introduction

Mechanized excavation, such as the use of roadheader, plough, shearer, and continuous miners, has gained considerable attention over the past few decades. Roadheaders (RH) are widely used for driving civil tunnels and underground mine drifts, owing to their operational flexibility, reduced vibration, lower capital and maintenance costs, and ability to efficiently cut rock formations with compressive strength up to 150-160 MPa (Copur et al. 1998). These advantages make the prediction of roadheader performance an important task for estimating project duration and cost. Researchers have made several attempts over the past years to establish prediction models for estimating roadheader performance by evaluating its instantaneous cutting rate (ICR), which is defined as the volume or tons of rock excavated per time of cutting (m^3/hr or tons/hr). Several approaches have been used to estimate the ICR of roadheader. Some researchers based their predictions on intact rock properties such as the uniaxial compressive strength (UCS) and/or Brazilian tensile strength (BTS) (Gehring 1989; Thuro and Plinninger 1999; Çopur et al. 2001; Balci et al. 2004; Keles 2005; Tumac et al. 2007; Ocak and Bilgin 2010; Kahraman and Kahraman 2016), while others included RH power and specific energy in their models (Rostami et al. 1994; Balci et al. 2004; Comakli et al. 2014; Choudhary et al. 2017). Some researchers also estimated ICR using rock mass parameters such as rock quality designation, rock mass boreability index, and rock mass cuttability index (Bilgin et al. 1996; Ebrahimabadi et al. 2011). Besides laboratory properties of intact rock and rock mass features, in-situ stress distribution around the underground opening is also critical for excavation process, especially unstable ground condition encountered (Adoko et al., 2020). It is evident that performance analysis, including the estimation of ICR and cutting tool consumption, is a key issue in roadheader applications in both civil and mining engineering. Selected empirical models representing ICR estimation are summarized in Table 1.

Table 1. Summary of the widely accepted models for axial RH performance prediction.

No.	Equations	Rock type	RH type	References
1	$ICR = \frac{1739}{UCS^{1.13}}$	UCS is the only parameters. No specific rocks given	250 kW Axial RH	Gehring (1989)
2	$ICR = k \cdot \frac{P}{SE_{opt}}$	Different type of rocks, k is 0.45 for Axial RH and 0.55 for T-RH in general	LCM tests	Rostami et al. (1994)
3	$ICR = 0.28 \cdot P \cdot (0.974)^{RMCI}$ $RMCI = UCS \cdot \left(\frac{RQD}{100}\right)^{2/3}$	Sedimentary rocks from siltstone, mudstone to sandstone with some dyke	95 kW Axial RH	Bilgin et al. (1996)
4	$ICR = 0.8 \cdot \frac{P}{0.37 \cdot UCS^{0.86}}$(Eq.1) $ICR = 0.8 \cdot \frac{P}{0.41 \cdot UCS^{0.67}}$(Eq.2)	d=5 mm for (Eq. 1) d=9 mm for (Eq. 2) variety of chromite, copper ore, serpentinite, clay, sand, lime, silt stones, tuff, trona, gypsum etc.	LCM tests	Balci et al. (2004)
5	$ICR = 163.93 \cdot UCS^{-0.5737}$	Clayey lime, claystone, siltstone, coal, marl, tuff	112 kW Axial RH	Keles (2005)
6	$ICR = 109.25 \cdot UCS^{-0.7233}$	Limestone, sandstone, siltstone, andesite, diabase	90 kW Axial RH	Tumac et al. (2007)
7	$ICR = 30.74 \cdot RMBI^{0.23}$ $RMBI = e^{\frac{UCS}{BTS}} \cdot \left(\frac{RQD}{100}\right)^{3}$	Siltstone, sandstone, mudstone interfaces with coal seam	82 kW Axial RH	Ebrahimabadi et al. (2011)
8	$ICR = -8.95 \cdot \ln(NPI) + 55.4$ $UCS = 3.17 \cdot e^{0.025 \cdot NPI}$	Clayey limestone, coal, claystone, mudstone	112 kW Axial RH	Kahraman et al.(2019)
9	$ICR = 56.785 \cdot UCS^{0.097}$	Ignimbrites, pyroclastic volcano-sedimentary rocks	200 kW Axial RH	Comakli (2019)
10	$ICR = \left(\frac{P}{UCS}\right)^{1.252} \cdot \left(\frac{\alpha}{RQD}\right)^{0.426}$	Limestone and Dolomite	260 kW Axial RH	This Study (2026)

Note:ICR: Instantaneous cutting rate; UCS: Uniaxial compressive strength; RMCI: Rock mass cuttability index; P: Power; SE_{opt}: Optimum Specific Energy; k: Constant coefficient; RPI: Roadheader penetration index; NPI: Needle penetration index; RMBI: Rock mass brittleness index; BTS: Brazilian tensile strength; LCM: Linear Cutting Test; RH: Roadheader; RQD: Rock Quality Designation; α is the angle between the plane of weakness and RH direction.

Among the earliest attempts to estimate roadheader cutting performance using intact rock parameters, Gehring (1989) introduced a prediction model for an axial and transverse type roadheader. Thuro and Plinninger (1999) investigated the influence of geological and geotechnical parameters on the cutting performance of 132 kW roadheader in the Zeulenroda sewage tunnel, introducing an ICR model as a function of the UCS. Çopur et al. (2001) developed a model for optimum specific energy of a RH in a chromite mine in Turkey. Tumac et al. (2007) also proposed some ICR models based on hardness values and intact rock UCS. In a comparative study on the performance of different excavation methods, Ocak and Bilgin (2010) also developed an ICR model based on UCS. Their findings further emphasized that performance prediction models should consider orientation and frequency of discontinuity in rock mass. The model developed by Rostami et al. (1994), which estimates ICR based on machine cutting power and SEopt, is often regarded as an accurate model. Also, Comakli et al. (2014) examined the RH performance and conical pick cutter consumption for different ore types.

Most models developed in the literature are based on RH power and intact rock strength, such as UCS and BTS. However, it is well known that fracture frequency and orientation of discontinuities within the rock mass also have a significant influence on RH performance, cutter consumption, and project scheduling, and therefore should be properly considered from the early stages of excavation projects. In this study, a preliminary data processing and RH performance evaluation framework is presented as a basis for the development of new empirical models for predicting the instantaneous cutting rate of RH.

2 Excavation Project

This study is conducted based on the project located in Guiyang, the eastern part of the Yunnan-Guizhou plateau in southwest China (Guo et al. 2024). This area has one of the largest karst landscapes in the world, and its geological setting has a direct influence on underground construction such as metro, waste disposal storage, tunnel excavation (Liu et al. 2022). Guiyang has a complex geological structure with widely distributed folds and faults trends in the north-south and northeast directions. Repeated tectonic activities over time have fractured the rock mass, creating favourable conditions for karst development (Liu et al. 2022). Limestone and dolomite, which belong to the variety of regional formations, are the main rocks present in the Guiyang rail transit (Guo et al. 2024). Visual and observational characteristics of those weak rocks are summarized in Table 2.

Table 2. Characteristics of major rock types in the study area(Guo et al. 2024; Liu et al. 2022).

Observed features	**Limestone**	**Dolomite**
Color	Gray to gray black	Grayish white to flesh red
Geological formation	Maokou formation (lower Permian) Daye formation (lower Triassic)	Maokou formation (lower Permian) Anshun formation (Triassic)
Structure	Cryptocrystalline, thin to medium thick layered	Medium to thick layered with fine to coarse grains
Local variation	Small amounts of mud along joint surfaces	Transitions locally into dolomitic limestone or argillaceous dolomite
Joint features	Micro tension, aperture of 1 – 4 mm with calcite vein filling	Micro tension, mostly opened with aperture of 1 – 3 mm and only a few closed.

The most significant geological challenge in this area is the presence of underground karst. Karst features include caves and varying conditions of fractures, with some filled with clay or breccia soil, and others partially filled, or completely empty (Guo et al. 2024). This variability makes it difficult to predict ground conditions ahead of excavation.

In the project, Roadheader which is EBZ260 is utilized for the aim. It is open type axial RH with 260 kW power and 92 tons weight respectively. It could be classified as heavy weight RH according to the classification (Bilgin et al. 2014) as described in following section.

3 Datasets

In this paper, the raw data including field, laboratory, and RH parameters obtained from a 4 km metro tunnel in Guiyang Rail Transit is examined, and the dataset is developed. A total of 1,755 datapoints (stations) were obtained. However, due to the repetition of rock property measurements across multiple stations, the dataset was aggregated based on the frequency of identical rock properties.Specifically, when multiple stations exhibited the same rock properties but different ICR values, the rock properties and the corresponding ICR values were averaged. Through this process, the dataset was reduced from 1,755 to 164 representative data points. The statistical distribution of data and relevant properties, including intact rock, rock mass, and RH specifications, are given in Table 3. Further, the specification of the RH used for metro excavation is presented in Table 4.

Table 3. Statistical summary of the parameters in aggregated database.

Description	UCS (MPa)	BTS (MPa)	Kv	BQ	RMR	BI	Alpha (degree)	RQD (%)	P (kW)	W (kN)	ICR (m^3/hr.)
Count	164	164	164	164	164	164	164	164	164	164	164
Maximum	66.35	4.27	0.52	419.05	50.93	19.38	70.00	48.00	260	905	25.00
Minimum	23.65	1.56	0.33	243.62	20.02	11.29	37.00	27.13	260	905	2.29
Average	45.01	3.02	0.44	334.60	36.06	15.02	51.03	36.53	260	905	11.66
Std	9.37	0.68	0.04	37.14	6.54	1.52	8.54	4.50	0.00	0.00	5.46

Note:ICR: Instantaneous cutting rate; UCS: Uniaxial compressive strength; BTS: Brazilian Tensile Strength; Kv: Rock mass integrity factor; BQ: Basic Rock Quality Index; RMR: Rock Mass Rating; BI: Brittleness Index; α is the angle between the plane of weakness and RH direction; RQD: Rock Quality Designation; P: Power of RH; W: Weight of RH

Table 4. Specifications of roadheader used in case study.

RH parameters	Axial RH (EBZ260)
Machine dimension (m)	12 · 2.77· 2.03
Diameter of opening (m)	6 · 5
Machine weight (kN)	905
Machine power (kW)	487
Cutting power (kW)	260
Power supply voltage (V)	1140
Cutting range (m)	6 · 5
Cutting rigidity (MPa)	100
Cutterhead rotating speed (RPM)	27 – 54
Conveyor belt speed (m/min)	66
Required water supply pressure (MPa)	3 – 8



4 Model Development

In data science and applied engineering, a key step before developing predictive models is data partitioning. Typically, 80% of the data is used for training and 20% for testing, which provides a balance between a large training set for the model and a sufficient testing set to evaluate its performance. Consequently, developed dataset with 164 datapoint is divided into 132 training and 32 testing data. Influence of each input variable on the ICR of the RH is examined and then inputs were chosen among the available feature of intact rock, rock mass, and RH specifications.

To find the best model, numerous linear multiple regression (LMR) and non-linear multiple regression (NLMR, with 50 different alternatives) models were developed using input parameters, including intact rock, rock mass properties, as well as machine specifications. Based on the developed models utilizing a variety of regression techniques, the most accurate output is obtained as a function of UCS, discontinuity orientation (α), RQD, and machine cutting power as presented in Eq.3.

$$\mathrm{ICR} = \left(\frac{\mathrm{P}}{\mathrm{UCS}}\right)^{1.252} \cdot \left(\frac{\alpha}{\mathrm{RQD}}\right)^{0.426} \quad (1)$$

The accuracy of the equation is validated using different statistical indices such as coefficient of determination (R^2 = 0.723 for training and 0.7425 for testing), root mean square error (RMSE = 2.84 and 2.91, respectively), and variance accounted for (VAF = 74 and 72.3, respectively). It is well known that the nature and rock mass condition in the field are not homogeneous or isotropic; therefore, the relationships between the input variables and the ICR may not be simple. Consequently, the prediction model cannot be represented by a single. After examining the alternative models developed (Eq. 3), the most suitable model and its corresponding output are presented in Figure 1. More, amount of error between measured and estimated ICR for each data point is presented in Figure 2 to show the variation of error along the excavation direction.

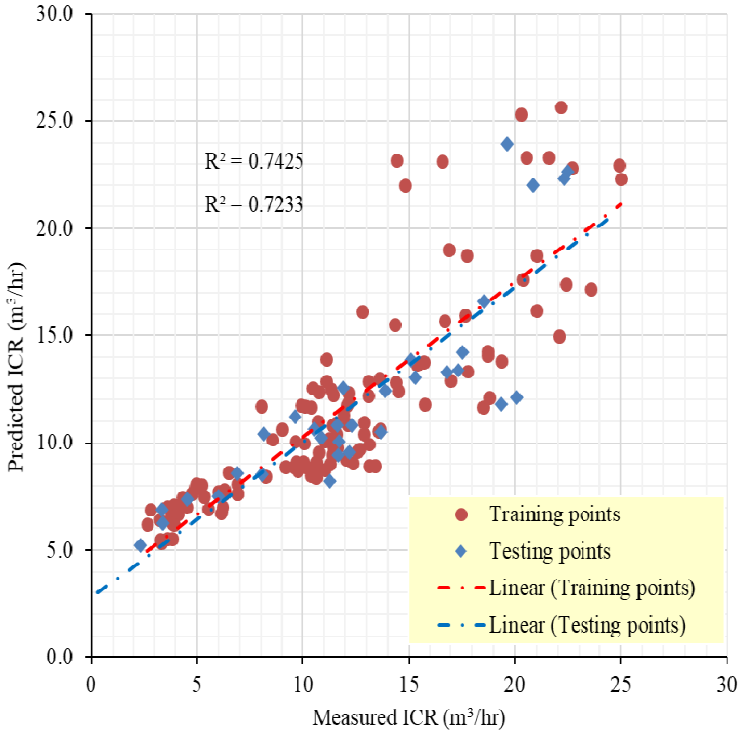


Fig.1 Relations of actual ICR with predicted ICR for both training and testing data.

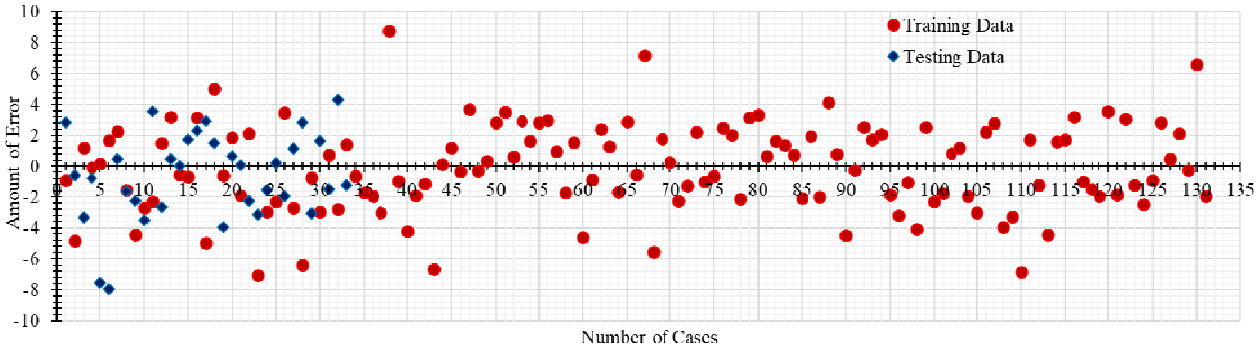


Fig 2. Amount of error between measured ICR and estimated ICR for developed model.

5 Conclusion

In this study, numerous LMR and NLMR models were developed using a large dataset comprising 1,755 data stations collected along a 4 km metro tunnel excavated with an RH. The accuracy of these models was evaluated using several statistical indices. It was found that the proposed nonlinear equation (Eq. 3) is the most accurate among them, due to the quality and range of input variables

representing intact rock, rock mass properties, and RH specifications. However, it should be noted that this research is ongoing, and more detailed data analysis and alternative modelling techniques will be applied using different methods to develop a more practical equation and a more accurate model for both industry and academia. In conclusion, the performance analysis of RH and cutter tool consumption is a nonlinear problem. Therefore, relying solely on single rock strength parameters (e.g., UCS, BTS) and machine power may not be sufficient. Instead, the orientation of discontinuities and fracture frequency in the rock mass should also be considered as input parameters to enable proper project scheduling and ensure completion within the planned time and budget.

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