

Research Article

A New Evaluation Method for the Uniaxial Compressive Strength ahead of the Tunnel Face Based on the Driving Data and Specification Parameters of TBM

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Uniaxial compressive strength (UCS) is a very important fundamental mechanical parameter for TBM construction. In this work, a predictive model of UCS was proposed according to the TBM parameters including torque, penetration, cutter number, and cutter diameter. The parameter of the new proposed model was established by fourteen existed TBM tunnels' construction data. To describe the relationships of UCS with PLSI of the Murree tertiary hard rocks, regression analyses have been conducted and a fitting equation with high-prediction performance was developed. Validation from the data of Neelum-Jhelum (NJ) TBM diversion tunnel were carried out. The absolute errors between predictive UCS and experimental UCS were presented. Through comparison, it can be concluded that the proposed calculation equation of UCS has a high accuracy for a certain rock type with UCS from 50 MPa to 200 MPa. For special hard rock or soft rock, a new calculation equation between UCS and TBM parameters should be studied furthermore.

1. Introduction

At present, nearly 200 long and deep-buried tunnels with length approaching or exceeding 10 km have been built in the fields of transportation, water conservancy, hydropower, and urban sewage disposal all over the world. Encouraged by the opening of Japan's Sei-kan tunnel (50.5 km in length) and the British-French submarine tunnel (53.9 km in length), a large number of larger scheme extralong tunnels have been planned in China and abroad, for example, the Japanese-Korean submarine tunnel between Fukuoka and Busan (250.0 km), Gotthard railway tunnel in Switzerland (56.9 km), and the Basis Brenner railway tunnel between Austria and Italy (55.0 km). Compared with traditional techniques such as drilling and blasting, the full-face rock tunnel boring machine (TBM) has gradually become

the first choice for long and deep tunnel construction in recent years since it has many advantages, such as high quality, high efficiency, environmental protection, and small disturbance of surrounding rock [1, 2]. As one of the most fundamental mechanical parameters, UCS has widely been applied in the process of TBM construction including assessment of rockmass rating (RMR) and Q_{TBM} rockmass system, hazard assessment of rockburst classification or TBM jamming and assessment of the reasonable supporting design [3–6]. Therefore, it is very important to quickly and accurately obtain the in situ UCS characteristics of the surrounding rock [7, 8].

The studies on determining the rock strength mainly focused on the direct standard laboratory uniaxial compressive tests and indirect tests such as the point load strength index (PLSI) [9]. A number of researchers have attempted to provide

empirical index-to-strength conversion factors between the UCS and PLSI, to reveal their correlation and demonstrate the practical application [4, 10–21]. Linear, power, logarithmic, and exponential equations correlating the UCS to the PLSI are summarized in Table 1.

However, one of the drawbacks for TBM construction is that the design prevents the direct observation near the tunnel face since TBMs excavate the entire face [22]. Due to the comprehensive cover and narrow space, it is impossible to carry out the standard laboratorial uniaxial compressive test in practical application. The previous testing methods on in situ rock strength were difficult to be applied timely and effectively. Therefore, some beneficial attempts have been carried out by different researchers based on the relation between the rock strength and TBM performance. Nelson et al. [23] founded the rock strength is proportional to the field penetration index (FPI). Sanio [24] found strong correlations between UCS and the specific energy (SE) defined as the amount of energy needed to excavate a unit volume of rock. Fukui and Okubo [22] suggested a method for calculating rock strength at the face from the cutting force exerted by the TBM, based on the results of laboratory experiments. A good consistency was found between the rock strength estimated from the cutting force, the Schmidt hammer rebound hardness, and other rock properties. Hamidi et al. [25] founded the UCS is proportional to the field penetration index (FPI), in which the highest R^2 value is 0.70. Based on data obtained from main tunneling projects in Iran, Hassanpour et al. [26–28] evaluated the relationship between UCS and actual TBM performance and results demonstrated that FPI and UCS were positive in correlation logarithmically.

The above studies have greatly promoted the development of the relationship among the UCS, PLSI, driving data, and specification parameters of TBM, but there are still obvious shortcomings in this area: first, most of the previous studies are based on qualitative or semiquantitative description of laboratory tests and did not give a general quantitative formula for engineering; second, the factors considered are relatively single, only through a specific TBM project, which means the operability and universality in engineering practice need to be improved.

Based on these findings, this work was organized as follows: a predictive model of UCS was proposed according to the TBM parameters such as torque, penetration, cutter number, and cutter diameter in Section 2. And then, the parameter of the new proposed model was established by fourteen existed TBM tunnels' construction data in Section 3. After that, the validation was carried out in Section 4. Finally, some conclusions were presented in Section 5.

2. A Predictive Model for the Uniaxial Compressive Strength

A large number of laboratory and in situ tests show that the relationship between normal thrust pressure and penetration of TBM can be described as a power function form, which can be expressed as follows [24]:

TABLE 1: Equations correlating the UCS to PLSI.

References	Expression
Broch and Franklin [4]	UCS = $24I_{s(50)}$
ISRM [10]	UCS = $(20 - 25)I_{s(50)}$
Norbury [11]	UCS = $(8 - 54)I_{s(50)}$
Tsidzi [12]	UCS = $(14 - 82)I_{s(50)}$
Grasso et al. [13]	UCS = $25.67I_{s(50)}$
Singh and Singh [14]	UCS = $23.37I_{s(50)}$
Kahraman [15]	UCS = $23.6I_{s(50)} - 2.7$
Lashkaripour [16]	UCS = $21.4I_{s(50)}$
Quane and Russel [17]	UCS = $24.4I_{s(50)}$
Kahraman et al. [18]	UCS = $24.8I_{s(50)} - 39.6$
Diamantis et al. [19]	UCS = $21.5I_{s(50)} - 6.02$
Kohno and Maeda [20]	UCS = $16.5I_{s(50)}$
Azimian et al. [21]	UCS = $56.94 \ln I_{s(50)} - 1.66$

$$F_N = \alpha \cdot P^{0.5} \cdot \sigma_c, \quad (1)$$

where F_N is the normal thrust force of TBM, kN; σ_c is the UCS of the surrounding rock, MPa; P is the penetration, which is a ratio of injection depth and rotation rate of TBM, mm/rev; and α is an empirical coefficient.

Bilgin et al. [29] suggested that the total torque of TBM can be calculated from the following formula:

$$T_R = \frac{1}{4} N_c \cdot F_R \cdot D_{TBM} \cdot f_L, \quad (2)$$

where T_R is the total torque of the TBM cutter head, kN·m; F_R is the mean rolling force of one cutter, kN; D_{TBM} is the cutter head diameter of the TBM, m; f_L is the coefficient for the frictional losses, 1.2 is used in this work; and N_c is the number of the cutters.

Furthermore, Sanio [24] suggested that the ratio of rolling force to normal thrust force is proportional to $P^{0.5}$ based on theoretical analysis and laboratory experiments, which can be written as

$$\frac{F_R}{F_N} = \frac{4}{5} \cdot \left(\frac{P}{D_{TBM}} \right)^{0.5}. \quad (3)$$

Substituting equations (1) and (3) into equation (2), the relationship among the UCS of the surrounding rock σ_c , penetration, cutter number, and cutter diameter of the TBM can be obtained, that is,

$$\sigma_c = \frac{5}{\alpha f_L} \cdot \frac{T_R}{N_c \cdot P \cdot D_{TBM}^{0.5}}. \quad (4)$$

Assuming $\lambda = (5/\alpha f_L)$, equation (4) can be rewritten as

$$\sigma_c = \lambda \cdot \frac{T_R}{N_c \cdot P \cdot D_{TBM}^{0.5}}, \quad (5)$$

where λ is an empirical parameter.

3. Establishment of the Parameter of the Proposed Model

To obtain the empirical parameter λ in equation (5), driving data and specification parameters from 14 TBM tunnels were regressed and analyzed. The related data are list in Table 2.

TABLE 2: Driving data and specification parameters from 14 TBM tunnels.

No.	Tunnel names	TBM parameters			Excavation parameters	
		Cutter diameter (m)	Cutter number	Average rock strength (MPa)	Average penetration (mm/rev)	Average torque (kN·m)
1	Hiraya	0.394	19	76.8	6.8	210
2	Nikengoya	0.394	20	53.4	7.7	210
3	Doushi	0.3556	27	67	8.2	310
4	Ogouchi	0.3556	34	76.6	3.1	120
5	Shinyuyama	0.432	27	57.4	6.9	250
6	Maiko	0.394	37	140	3.2	470
7	Tsukui	0.432	37	84.7	5.9	590
8	Tolo	0.432	25	120	4.4	300
9	ChaiWan	0.4826	32	122.7	4.3	900
10	ZWCT	0.432	42	75	7	850
11	GWCT	0.432	32	135	5	900
12	Maen	0.432	36	130	4.2	850
13	PieveI	0.432	27	156	3	541
14	Varzo	0.432	27	135	5.5	558

With data in Table 2 and equation (5), the empirical parameter λ for each tunnel engineering was calculated. After that, the relationships between λ and torque, penetration, cutter number, and cutter diameter were analyzed, which are shown in Figures 1–4. From these four figures, it is shown that the correlations between λ and penetration P and cutter number N_c are very small and the regression coefficients are less than 20%. The correlation between λ and TBM diameter is obvious, but small with a regression coefficient of 55.39%. The correlation between λ and torque T_R is the biggest with a regression coefficient of 84.08%. Thus, the regression equation from T_R was used to calculate the empirical parameter λ as follows:

$$\lambda = 14.73 \cdot (T_R)^{-0.464}. \quad (6)$$

Substituting equation (6) into equation (5), the final expression of the relationship among the UCS of the surrounding rock σ_c , torque, penetration, cutter number, and cutter diameter of the TBM can be rewritten as follows:

$$\sigma_c = 14.73 \cdot \frac{(T_R)^{0.536}}{N_c \cdot P \cdot D_{TBM}^{0.5}}. \quad (7)$$

It can be seen from equation (7) that the influencing factors of UCS can be classified into four groups: torque, penetration, cutter number, and diameter of the TBM.

4. Validation from the Data of the Neelum–Jhelum (NJ) TBM Diversion Tunnel

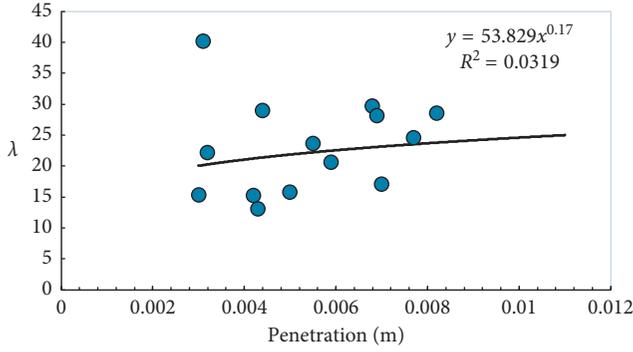
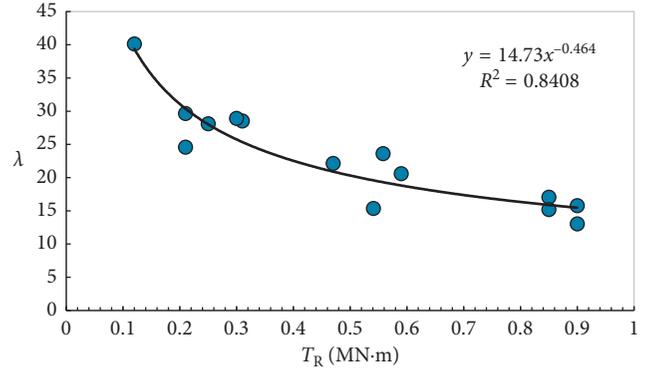
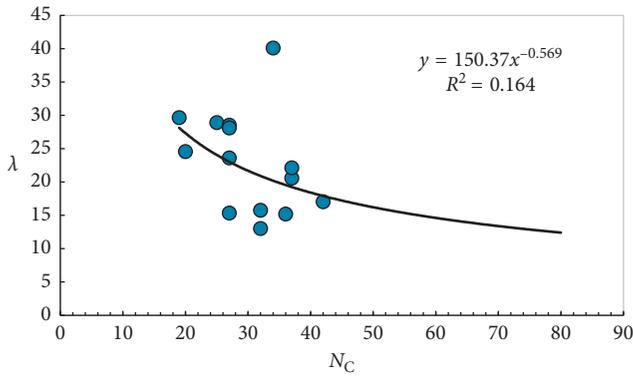
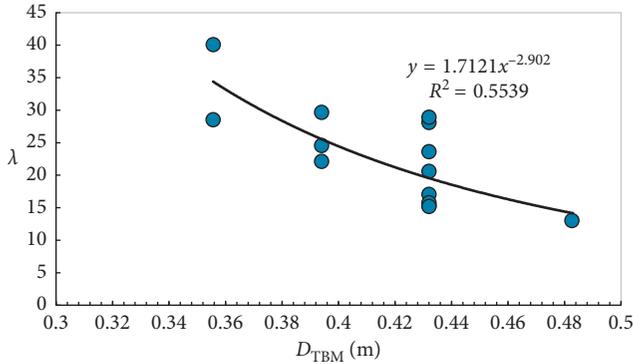
4.1. Project Description of the Neelum–Jhelum TBM Diversion Tunnel. The Neelum–Jhelum hydroelectric project is located in the Muzaffarabad district of Azad Jammu and Kashmir (AJK), Pakistan. A 19.6 km stretch of the tunnel from the Nauseri site will be constructed as a twin tunnel system, each with a cross section of about 52 m²; 11.2 km of the twin tunnel system will be excavated by using the Herrenknecht gripper TBM and the remainder by drilling and blasting. Figure 5 shows the picture of the TBM which excavated the NJ TBM diversion tunnels, and the main technical specifications of TBM are summarized in Table 3.

The diversion tunnel is located in the Himalayas, geologically young mountains with spectacular heights developed as a result of collision between various continental and microcontinental plate fragments during the late Mesozoic to late Cenozoic periods. The main geological formation outcropped in the project area is the Murree Formation except at the intake, which is partly in igneous or metamorphic rocks belonging to the Panjal Formation. Geological mapping of each TBM and drill and blast tunnel is conducted continuously as the tunnel advances. The Murree Formation consists of alternating beds of grey medium to fine-grained sandstone and reddish colored fine to very fine grained siltstone with occasional thin mudstone layers. Contacts are often gradational with no bedding parting. Sandstone, siltstone, and occasional thin mudstone beds are recognized. Thick sandstone beds are often very massive and competent.

4.2. Estimation of UCS from PLSI. As mentioned before, one of the drawbacks for TBM construction is that the design prevents the direct observation near the tunnel face since TBMs excavate the entire face [22]. Due to the comprehensive cover and narrow space, it is impossible to carry out the standard laboratorial uniaxial compressive test in practical application. Thus, in this work, a batch of typical rock samples were collected at first and were cut into a $\Phi 50 \times 100$ mm standard cylindrical specimen, which can be seen in Figure 6. Then, the standard laboratorial uniaxial compressive tests and point load tests were carried out to establish the relationship between them.

The UCS was determined using the RMT~201 rock test machine according to the ASTM standards, which can be seen in Figure 7. Its maximum load is 1 MN, and its maximum confining pressure is 50 MPa. The loading rate was set at 0.05 mm/s, and more details about the test machine can be seen in [30, 31].

The point load tests were carried out using the point load testing machine with a digital display, as shown in Figure 8. In order to make rock test results with different sizes more scientific, it is necessary to establish corrected the point load

FIGURE 1: Relationship between λ and penetration.FIGURE 4: Relationship between λ and torque.FIGURE 2: Relationship between λ and cutter number.FIGURE 3: Relationship between λ and TBM diameter.

strength index (PLSI), which can be obtained from the following equation:

$$\text{PLSI} = FI_s, \quad (8)$$

$$F = \left(\frac{D_e}{50}\right)^{0.45},$$

where I_s is the uncorrected point load strength index, F is the correction factor, and D_e is the equivalent circle diameter of the destroyed cross-sectional area.

The proper correlation between the UCS and PLSI is one of the most critical concerns in applying the point load test.

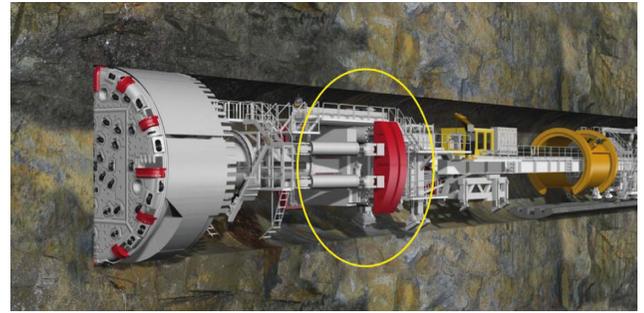


FIGURE 5: Gripper TBM used for the excavation of NJHP tunnel.

TABLE 3: Main specifications of the Steg and Raron TBMs.

Parameter	Value
Diameter	8.53 m
Maximum thrust force	27,489 kN
Maximum torque	8825 kN m
Number of cutters	58
Cutter diameter	19" (432 mm)
Cutter spacing	90 mm
Maximum cutter force	350 kN
Maximum revolutions per minute (RPM)	9

The raw dataset was subjected to least squares regression analysis. In this work, linear ($\text{UCS} = KI_{s(50)} + b$), exponential ($\text{UCS} = Ke^{b \cdot I_{s(50)}}$), logarithmic ($\text{UCS} = K \ln(I_{s(50)}) + b$), and power ($\text{UCS} = KI_{s(50)}^m$) curve fitting approximations were executed, and the approximation equations with highest R^2 were determined for each regression. Figure 9 shows the plot of the UCS versus the PLSI for 100 rock samples (50 sandstones and 50 siltstones). The empirical conversion equations between UCS and PLSI are also presented in Figure 9 and Table 4. It can be seen that when the value of PLSI is between 1.5 and 5 MPa, the predictive results from the four regressions have a great agreement. When the PLSI value is lower than 1.5 MPa or larger than 5.0 MPa, the deviation of exponential and logarithmic regression types are relatively larger than that of the other types. Based on the best correlation coefficient (R^2) of 0.9114, the new



FIGURE 6: The part of the samples for uniaxial compressive tests.

power equation (Table 4) applied in the tertiary sandstone and siltstone of the Murree Formation was chosen.

In addition, the predicted values were drawn versus the measured values by using a 1:1 slope line, as shown in Figure 10. It can be seen that the predicted results are in good agreement with the measured ones, and all the dataset lies exactly on a straight line without scatter, which indicated that PLSIs are reliable values for estimating UCS, avoiding the cumbersome and time-consuming standard laboratorial test carried out in the preliminary studies.

4.3. Validations. The in situ point load strength was manually recorded every day, and then the UCS of surrounding rock in the Neelum–Jhelum TBM diversion tunnel can be obtained with Table 4. Figure 11 is the UCS from in situ point load tests at different identified geological area along the TBM tunnel alignment regarded as actual UCS. From Figure 11, it can be seen that the rock strength varied from 24.38 MPa to 228.32 MPa and the average UCS is 131.83 MPa. It can be concluded that the rock type varied along the tunnel alignment from the moderately to closely jointed siltstone (UCS < 120 MPa) to primarily massive and blocky sandstone (UCS > 150 MPa).

The TBM performance database was collected during construction phases, where the geological conditions and machine performance information were valid. As shown in equation (7), four parameters were involved here: cutter number, TBM cutter diameter, penetration, and torque. Figure 12 is the recorded torque along the Neelum–Jhelum TBM diversion tunnel in the conduction process. From Figure 12, it found that the maximum torque is 2.8 MN·m at 07+700.99 section where the estimated UCS from is 148.46 MPa. The minimum torque is 0.6 MN·m at 07+555.42 section where the estimated UCS is 48.74 MPa,

which means that more torque is needed for a hard rock than a soft rock with the same penetration.

Figure 13 is the recorded penetration along the Neelum–Jhelum TBM diversion tunnel in the conduction process. It can be seen that the maximum penetration is 15 mm at three sections where the estimated UCS from laboratory tests is 105.4 MPa, 48.7 MPa, and 42.96 MPa. The minimum penetration is 4.5 mm at 07+645.03 section where the estimated UCS from laboratory tests is 198.39 MPa. From the above data, it can be concluded that the penetration is not determined by rock strength.

With the data from Figures 12 and 13, equation (7) was used to calculate the UCS from TBM parameters at different construction time. Then, the calculated UCS was compared with the estimated UCS from laboratory tests which is shown in Figure 14. From Figure 14, it is shown that the calculated UCS from T_R in equation (7) agrees with that from laboratory tests, even though there is some difference. When the actual UCS is over 200 MPa, the difference between calculated UCS from T_R and actual UCS is much more obvious. This means that equation (7) seems more suitable for tunnels with a lower UCS less than 200 MPa. This is because that equation (7) is conducted from 14 TBM tunnels list shown in Table 2 where all the UCS is lower than 200 MPa.

To further analyze the errors between calculated UCS and actual UCS, the following formula was adopted to calculate the absolute errors:

$$E(\%) = \left| \frac{\sigma_{\text{actual}} - \sigma_{\text{prediction}}}{\sigma_{\text{actual}}} \right| \cdot 100, \quad (9)$$

where $E(\%)$ is the absolute error; σ_{actual} is the actual UCS that was obtained by in situ tests; and $\sigma_{\text{prediction}}$ is the predictive UCS that was obtained by using equation (7).



FIGURE 7: RMT~201 rock test machine.



FIGURE 8: The point load testing machine.

The results of absolute errors are presented in Figure 15. From Figure 15, it shows that the maximum absolute error is 34.32% and the minimum absolute error is 0.07%. The average absolute error is 8.28%. There are 5 sections (only 1% sections) with an absolute error higher than 20%. This means that the calculated UCS agrees with that from the indoor tests. At these five sections, the actual UCS values are 180.39 MPa, 138.31 MPa, 223.45 MPa, 24.38 MPa, and 46.35 MPa. When the actual UCS is 42.96 MPa, 48.74 MPa, 46.36 MPa, and 24.38 MPa, the absolute errors are 12%, 17%, 28%, and 34%, respectively. According to the above

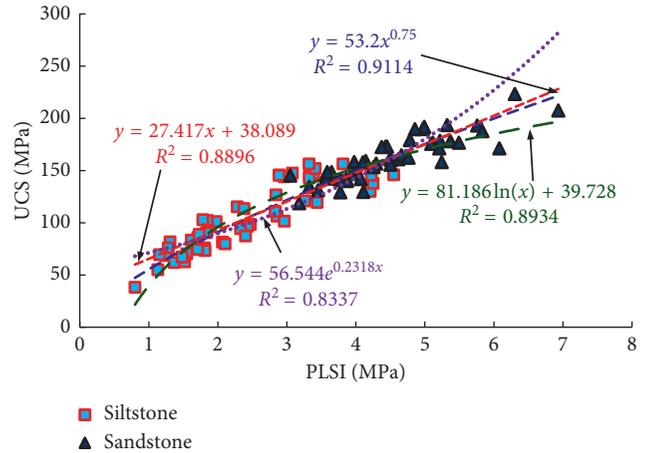


FIGURE 9: The relation between UCS and PLSI obtained from regression.

TABLE 4: The summary results of correlation between UCS and PLSI.

Regression type	Relationship	Regression coefficient
Exponential	$UCS = 56.5e^{0.23I_{s(50)}}$	0.8337
Linear	$UCS = 27.42I_{s(50)} + 38.1$	0.8896
Logarithmic	$UCS = 81.2 \ln(I_{s(50)}) + 39.7$	0.8934
Power	$UCS = 53.2I_{s(50)}^{0.75}$	0.9114

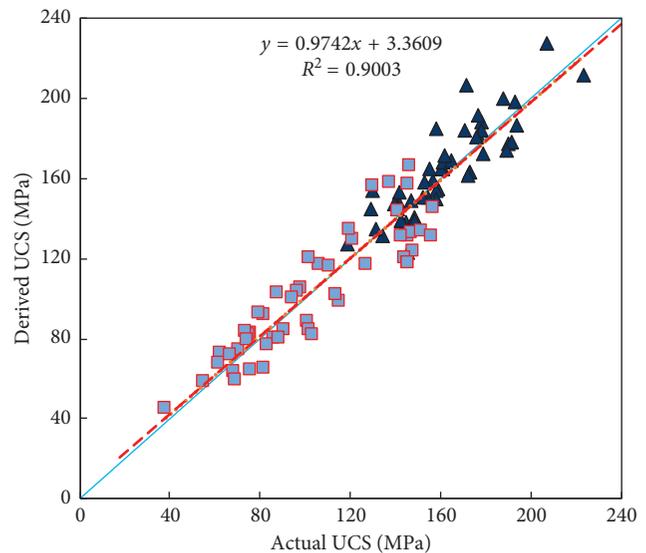


FIGURE 10: Cross correlation of actual and derived values of UCS from PLSI.

data, it seems that equation (7) has a low accuracy for situation with a high actual UCS or a low actual UCS. This is because that equation (7) is calculated from 14 TBM tunnels list in Table 2 where the UCS varied from 53.4 MPa to 156 MPa. If we can collect more data from different TBM tunnels, a regressed equation for different kinds of rock could be conducted with the proposed method here.

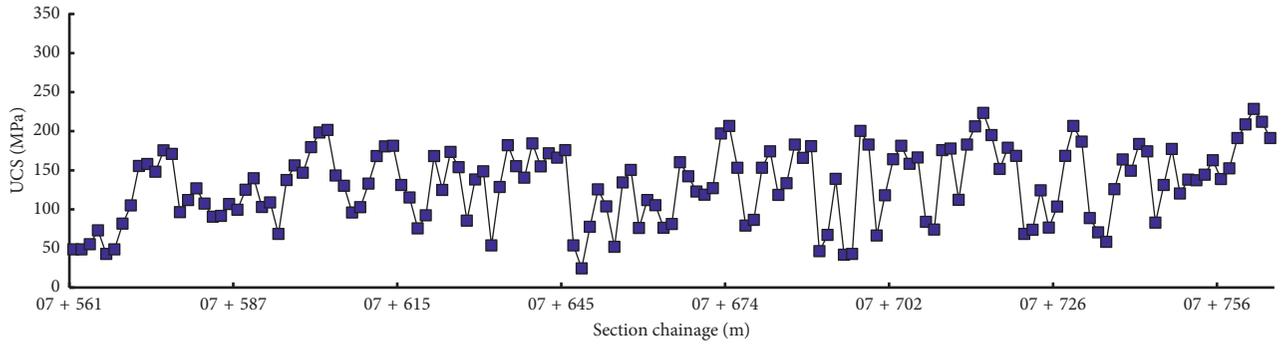


FIGURE 11: UCS values from laboratory tests along the Neelum–Jhelum TBM diversion tunnel.

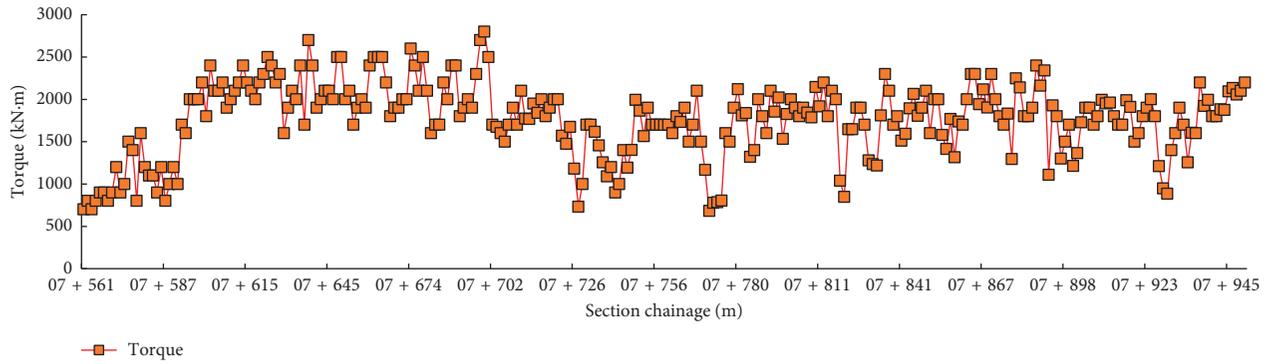


FIGURE 12: The recorded torque along the Neelum–Jhelum TBM diversion tunnel.

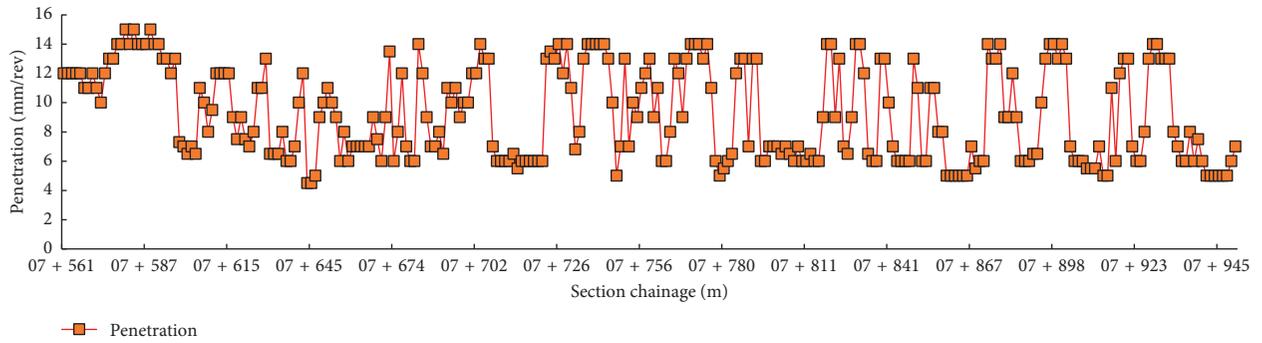


FIGURE 13: The recorded penetration along the Neelum–Jhelum TBM diversion tunnel.

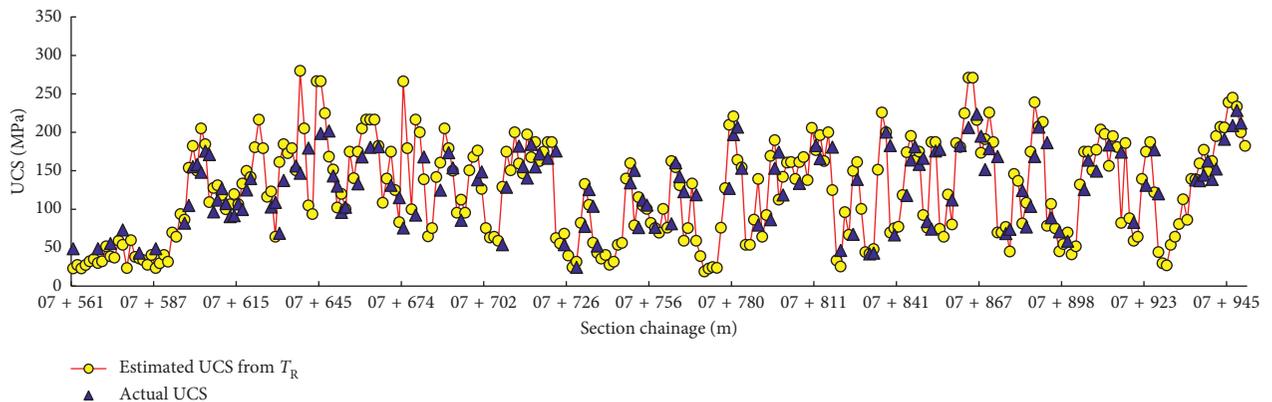


FIGURE 14: Comparisons between calculated UCS and experimental UCS.

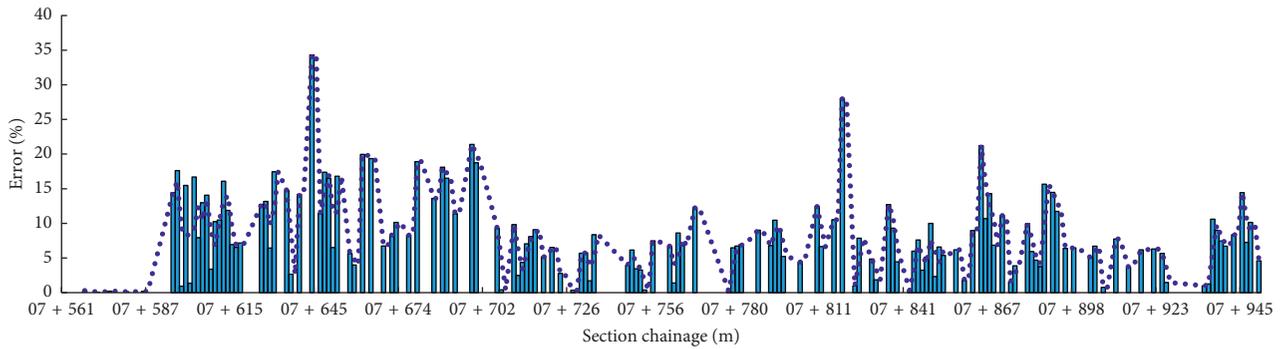


FIGURE 15: Error analysis graphics.

5. Conclusions

The uniaxial compressive strength (UCS) is a very important fundamental mechanical parameter for TBM construction. Nowadays, a large number of studies were carried out about the relationship among the UCS, PLSI, driving data, and specification parameters of TBM. But there are still several obvious shortcomings. In this study, a new evaluation method for the uniaxial compressive strength ahead of the tunnel face based on the driving data and specification parameters of TBM was proposed, and some conclusions were obtained, which can be given as follows:

- (1) A predictive model of UCS was proposed according to the TBM parameters such as torque, penetration, cutter number, and cutter diameter.
- (2) Based on the data from fourteen TBM tunnels, relationships between UCS and N_c , T_R , D_{TBM} , and P were studied. The results show that the correlation between UCS and T_R is strong with a correlation coefficient of 84.08%. Basing on this, the parameter of the new proposed model was established.
- (3) To describe the relationships of UCS with PLSI of the Murree tertiary hard rocks, regression analyses have been conducted and a fitting equation with high-prediction performance ($R^2 = 0.9114$) was developed.
- (4) Validation from the data of the Neelum–Jhelum (NJ) TBM diversion tunnel was carried out. The absolute errors between predictive UCS and experimental UCS were presented. Through comparison, it can be concluded that the proposed calculation equation of UCS has a high accuracy for a certain rock type with UCS from 50 MPa to 200 MPa. For special hard rock or soft rock, a new calculation equation between UCS and TBM parameters should be studied furthermore.

This study provides the technical strut for the later thorough research on the assessment of rockmass classification, rockburst, or TBM jamming. To apply the research of this study to engineering practices preferably, a software system of the in situ rock strength estimation considering the PLSI and TBM performance will be developed as well in the subsequent study. Then, combining with the proposed rockburst or large extrusion deformation criteria, the security status of the tunnel face will be evaluated in real time.

Data Availability

No additional data are available.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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