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Correction of Point Load Strength on Irregular Carbonaceous Slate in the Luang Prabang Suture Zone and the Prediction of Uniaxial Compressive Strength

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Abstract: Uniaxial compressive strength (UCS) testing requires high-quality core samples, which is a difficult task for weak, highly fractured, thinly bedded, foliated, and weathered rocks. In addition, it is time-consuming and expensive. Because of the good relationship between rock point load strength (PLS) and UCS, the PLS could be used to estimate rock UCS quickly. The lump structure and layer structure of carbonaceous slate are revealed in the tunnels of the China–Laos Railway in the Laos Luang Prabang Suture Zone as one of the important factors leading to tunnel squeezing deformation and support structures. To reveal the relationship between the PLS and UCS of carbonaceous slate in the Luang Prabang Suture Zone, PLS tests and UCS tests of lump-structure carbonaceous slate (lamina plane inconspicuous) and layer-structure carbonaceous slate (lamina plane conspicuous) were performed. Results show that the $I_{s(50)}$ of lump-structure carbonaceous slate ranged from 0.06 MPa to 0.30 Mpa, the $I_{s(50)}$ of layer-structure carbonaceous slates which were loaded perpendicular to the lamina plane ranged from 0.64 MPa to 1.25 MPa, the $I_{s(50)}$ of layer-structure carbonaceous slates which were loaded parallel to the lamina plane ranged from 0.49 MPa to 0.71 MPa, and the correction power index m ranged from 0.42 to 0.51 with an average value of 0.47. Four correlation expressions of carbonaceous slate relationships between PLS and UCS were fitted by zero-intercept linear expression, nonzero intercept linear expression, power expression, and logarithmic expression, and the calculation results were compared with results calculated by the International Society of Rock Mechanics (ISRM) correlation equation. It is concluded that the correlation equation between UCS and PLS recommended by ISRM specifications easily causes soft rock strength overestimation, which affects the correct evaluation of the surrounding rock property and the structural design safety of tunnels and underground projects. The zero-intercept linear equation UCS = $18.45I_{s(50)}$ has better goodness of fit and higher accuracy in predicting the UCS of the carbonaceous slate in the Luang Prabang Suture Zone.

Keywords: Luang Prabang Suture Zone; carbonaceous slate; point load strength; uniaxial compressive strength; size correction factor

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1. Introduction

The Luang Prabang Suture Zone is located in the north-central part of Laos territory, which is the connection area of the Lanping–Simao terrane and the Indosinian terrane; it is named for the Luang Prabang Province of Laos [1–3], as shown in Figure 1. The China–Laos Railway crosses Laos Luang Prabang Suture Zone, and many tunnels have been built within the influence of the Luang Prabang Suture Zone. Affected by Luang Prabang Suture Zone, the tunnels' surrounding rock is an almost carbonaceous slate with low strength. Coupled with the serious influence of tectonic stress, the tunnels have caused the problem of squeezing deformation. The uniaxial compressive strength (UCS) of rock is an important rock mechanical parameter in rock engineering. It is crucial information to infer and determine the type and grade of tunnel squeezing deformation. However, UCS testing requires high-quality core samples of proper geometry. However, preparing high-quality cores, particularly from weak, highly fractured, thinly bedded, foliated, or weathered rocks is a difficult task. In addition, this test is time-consuming and expensive. By comparison, the point load strength (PLS) test operation is simple, the irregular rock can be used, it is convenient for field implementation, and the feasibility is relatively strong.

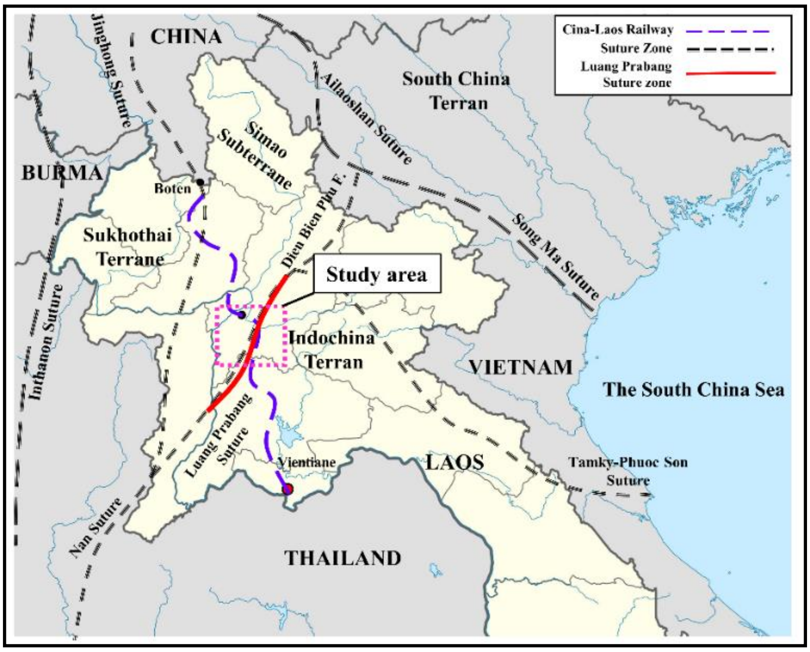


Figure 1. China–Laos Railway location and study area.

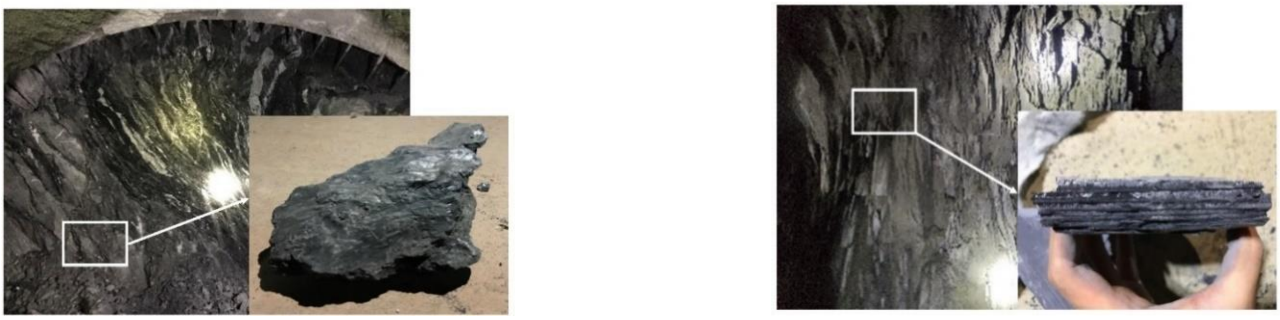
The PLS test method was first proposed by E. Broch and J. A Franklin [4]. Because of the correlation between PLS and UCS, PLS was also considered the optimum method for indirectly estimating the rock UCS. Based on related research, the International Society of Rock Mechanics (ISRM) proposed that the UCS of rock was equivalent to 20~25 times the PLS (ISRM, 1985). Many relevant scholars had performed studies on the relationship between rock PLS and UCS based on different rocks in different countries and regions [5–18]. At present, the linear correlation was most widely used in two types of strength conversion, and some researchers had also presented various expressions, such as power equations, exponential equations, logarithmic equations, and quadratic equations. In addition, relevant scholars had conducted relevant research on the failure mechanism and calculation method of PLS [19–22]. The failure mechanism of the point load test was based on the tensile stress failure concept at the loading point position [23,24]. The calculation method of the equivalent core diameter was widely adopted in the current PLS test. However, some relevant scholars still considered that the influence of the sample failure mechanism and the influence of the sample shape coefficient were much more significant [25,26].

According to recent research, the investigation of the correlation expressions between PLS and UCS is largely based on several types of rocks limited to a specific area, which has obvious regional applicability and rock type applicability. In addition, the correlation expressions of soft rocks (UCS $\leq$ 30 MPa) are rarely presented. Carbonaceous slate, as a common layered soft rock, and the relationship between PLS and UCS are rarely researched, and the traditional correlation expressions are inapplicable. The main objective of this study was to clarify the relationship between the PLS and UCS of carbonaceous slate, which is a typical soft rock found in the Luang Prabang Suture Zone, Laos. Based on a series of PLS tests and UCS tests of carbonaceous slate with different structures and different loading directions, the relationship between PLS and UCS is established by considering irregular samples and the size correction. The results could improve the accuracy of soft rock UCS estimating by PLS testing, and it will provide a design reference for soft rock engineering. It also will be beneficial to the prediction of the level of tunnel squeezing deformation.

2. Carbonaceous Slate Description and Sample Preparation

2.1. Carbonaceous Slate Description

The part of the China–Laos Railway located in the Luang Prabang Suture Zone is approximately 42 km, as shown in Figure 1. All of the sampling sites are located in this area in different tunnels in which surrounding rock is dominated by carbonaceous slate. The revealed carbonaceous slate is a typical metamorphic rock, and it has two different structure types, such as lump structure and layer structure, as shown in Figure 2. The lump-structure carbonaceous slate's (Figure 2a) compressive strength is very low, it can be crushed into pieces by hand, the lamina planes are inconspicuous, and it easily becomes soft in water. The layer-structure carbonaceous slate's (Figure 2b) compressive strength is slightly higher than the lump-structure carbonaceous slate, and the lamina planes are conspicuous. The geological age of the two types of carbonaceous slate is from Palaeozoic to Mesozoic. The color is dark grey. Affected by the mineral composition, lamina plane bonding degree, water content, weathering degree, and other factors, the compression strength is variable. Because of more intense geological tectonic activities, such as tensile, fracture, collision, and extrusion in the Luang Prabang Suture Zone, the development degree of rock fissures and the rock mechanical properties are more complex.



(a) (b)

Figure 2. Different structure types of carbonaceous slate: (**a**) lump structure; (**b**) layer structure.

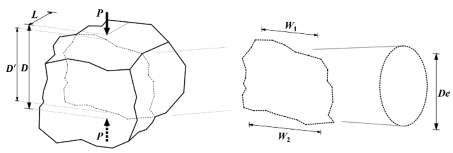
2.2. Sample Preparation

To obtain the correlation between UCS and PLS, A total of 16 different locations and 2 different structure types of carbonaceous slate were sampled for UCS testing and irregular rock PLS testing. The numbers of samples were a total of 700 rock samples for the PLS test and a total of 66 rock samples for the UCS test. Samples from the same location were used for the same UCS test and PLS test in order to minimize unexpected errors caused by the differential properties of samples from different spots, and the tests' invalid data were eliminated. The numbers of different locations' samples are shown in Table 1. The type of loading machine used in the PLS test is YSD-7. It consists of a load frame for applying loads up to 60 KN, on which a manual hydraulic jack is mounted. The specimens are loaded by two cone-shaped points. The applied load is measured by a pressure transducer.

Rock sample preparation, test methods, and calculation procedures followed the ISRM standard [27]. The width and height of irregular samples used for the PLS test were controlled between 50 ± 30 mm, and the size of D satisfied the conditional expression of $0.3W < D < W$ and $D < 2L$, as shown in Figure 3. Because of the samples with low strength, the loading penetration depth would affect the accuracy of test results. Therefore, the instantaneous distance between the loading points of rock sample failure D' was recorded as the basis of calculation. The numbers of each location are at least 30 samples.

Table 1. Numbers of different locations' carbonaceous slate samples.

Location Number	Structure Type	Loading Direction	PLS Test Numbers	UCS Test Groups
1	Lump structure	/	38	2
2	Lump structure	/	39	2
3	Lump structure	/	55	3
4	Lump structure	/	49	3
5-V	Layer structure	Perpendicular to lamina plane (⊥)	51	3
5-P	Layer structure	Parallel to lamina plane (‖)	35	2
6-V	Layer structure	Perpendicular to lamina plane (⊥)	36	2
6-P	Layer structure	Parallel to lamina plane (‖)	39	2
7-V	Layer structure	Perpendicular to lamina plane (⊥)	44	2
7-P	Layer structure	Parallel to lamina plane (‖)	42	3
8-V	Layer structure	Perpendicular to lamina plane (⊥)	47	2
8-P	Layer structure	Parallel to lamina plane (‖)	41	2
9-V	Layer structure	Perpendicular to lamina plane (⊥)	58	2
9-P	Layer structure	Parallel to lamina plane (‖)	42	2
10-V	Layer structure	Perpendicular to lamina plane (⊥)	43	2
10-P	Layer structure	Parallel to lamina plane (‖)	41	2



(**a**) Irregular sample of PLS test

Loading Failure Loading Failure

(**b**) (**c**)

Figure 3. Carbonaceous slate PLS test sample: (**a**) irregular sample of PLS test; (**b**) lump structure; (**c**) layer structure. Note: *P*: Failure load; *D*: Distance between two loading points; D': Instantaneous distance between two loading points of rock sample failure; *W*: Sample average width, $W = (W_1 + W_2)/2$; *De*: Equivalent sample diameter.

Rock samples used for the UCS test are cylindrical samples with 50 mm diameter and 100 mm height. However, as most carbonaceous slate's compression strength is low, cylindrical samples cannot be obtained by drilling the core, so a few cubic samples with a side length of 70 mm were used for the UCS test. The cylindrical samples were prepared by drilling the core in the surrounding rock, and the cubic samples were made by cutting and grinding. Each location has 2~3 groups for the UCS test, each group has 3 samples. Figure 4 shows the different samples for the UCS test. The type of loading machine used in the UCS test is a conventional machine that can only record the failure strength.

(**a**) (**b**) (**c**)

Figure 4. Carbonaceous slate UCS test samples: (**a**) UCS test sample loading direction; (**b**) cubic samples; (**c**) cylindrical samples. Note: *d*: Side length of cubic sample; *w*: Diameter of cylindrical sample; *h*: Height of cylindrical sample.

3. Test Data Statistics Analysis

3.1. Determination of PLS $I_{s(50)}$ of Irregular Lump Samples

For irregular rock samples for PLS testing, the uncorrected PLS index I_s is calculated using Equation (1), as suggested by the ISRM. The equivalent core diameter D_e should be calculated according to Equation (2):

$$I_s = P/D_e^2 \tag{1}$$

$$D_e{}^2 = 4WD'/\pi \tag{2}$$

where P is the failure load, W is the sample average width, D' is the instantaneous distance between two loading points of rock sample failure. The measurement error for W and D' should be within ±5% and ±2%, respectively.

The PLS index should be established as the strength value of the sample with a 50 mm D_e size ($I_{s(50)}$). The size correction factor F can be used to convert I_s to $I_{s(50)}$, and the revised calculation equation of $I_{s(50)}$ is proposed as follows:

$$I_{s(50)} = FI_s = \left(\frac{D_e}{50}\right)^m I_s \tag{3}$$

where m is the correction power index, which is related to rock properties.

Figure 5 shows the typical location of carbonaceous slate's relationship between P and $D_e{}^2$, and a straight line is used to fit the data of P and $D_e{}^2$. From the fitting line, the failure load P of the 50 mm D_e can be obtained. Then, the $I_{s(50)}$ can be calculated.

Table 2 shows the results of the PLS test. The determination coefficient R^2 of P- $D_e{}^2$ ranges from 0.69 to 0.85, showing a good correlation. The average determination coefficient of lump-structure carbonaceous slate is about 0.81, and the average determination coefficient of layer-structure carbonaceous slate, in which the loading direction is perpendicular to the lamina plane, is about 0.83. In contrast, the determination coefficient of layer-structure carbonaceous slate, in which the loading direction is parallel to the lamina plane, is slightly lower, with an average value of 0.76. The main reason is the difference in lamina plane bonding degree.

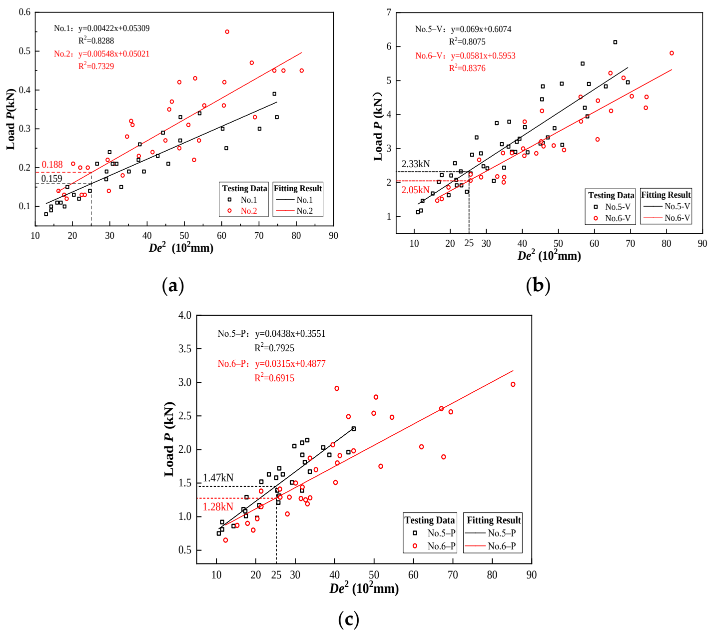


Figure 5. P-$D_e{}^2$ fitting curve of carbonaceous slate in the Luang Prabang Suture Zone: (**a**) Lump structure; (**b**) layer structure loaded perpendicular to lamina plane; (**c**) layer structure loaded parallel to lamina plane.

Table 2. Results of point load strength testing.

Location Number	Structure Type	Loading Direction	PLS $I_{s(50)}$ (MPa)	P-De^2 Determination Coefficient R^2	Correction Power Index m	ln(F)-ln(De/50) Determination Coefficient R^2
1	Lump structure	/	0.0635	0.8288	0.4427	0.4144
2			0.0751	0.7329	0.4222	0.3012
3			0.1942	0.8385	0.4548	0.4704
4			0.3052	0.8223	0.4569	0.3667
5-V	Layer structure	Perpendicular to lamina plane (⊥)	0.9328	0.8075	0.4553	0.3713
6-V			0.8191	0.8376	0.4516	0.5719
7-V			1.1196	0.8251	0.4598	0.4058
8-V			1.2503	0.8203	0.4639	0.4505
9-V			1.0424	0.8485	0.4696	0.4769
10-V			0.6416	0.7926	0.4763	0.4126
5-P	Layer structure	Parallel to lamina plane (‖)	0.5877	0.7994	0.4851	0.3468
6-P			0.5101	0.6915	0.4704	0.4036
7-P			0.7100	0.7379	0.5144	0.3288
8-P			0.6152	0.7943	0.4835	0.3526
9-P			0.4875	0.7486	0.4941	0.3319
10-P			0.5632	0.7784	0.4939	0.3571

The corrected PLS changes notably with carbonaceous slate structure and loading direction. For the lump-structure carbonaceous slate, the cracks extended gradually until the fracture plane was formed and rock failure occurred. The $I_{s(50)}$ range is from 0.06 MPa to 0.31 MPa, and the average is 0.16 MPa. For the layer-structure carbonaceous slate loaded perpendicular to the lamina plane, the surface of the sample was first crushed, and the brittle rock failure occurred directly. The $I_{s(50)}$ range is from 0.64 MPa to 1.25 MPa, and the average is 0.97 MPa. For the layer-structure carbonaceous slate loaded parallel to the lamina plane, tensile failure occurred along the weak lamina plane. The $I_{s(50)}$ is substantially affected by the lamina plane bonding force, the range is between 0.49 MPa and 0.71 MPa, and the average is 0.58 MPa.

3.2. Determination of PLS Correction Power Index of Irregular Lump Samples

According to the $I_{s(50)}$ that was obtained (Table 2), the correction power index m can be calculated by Equation (4). The fitting relationships between $\ln(I_{s(50)}/I_s)$ and $\ln(D_e/50)$ of typical location samples are shown in Figure 6.

$$m = \frac{\ln(I_{s(50)}/I_s)}{\ln(D_e/50)} \tag{4}$$

The determination coefficient of $\ln(F)$-$\ln(D_e/50)$ is quite low, but these results are similar to the experimental results of various rocks that had been explored by relevant scholars [7,28,29]. Therefore, this study's fitting relationships are reliable.

The results show that the m range is from 0.42 to 0.51. Among these, the m average for lump-structure carbonaceous slate is 0.44, for the layer-structure carbonaceous slate loaded perpendicular to the lamina plane it is 0.46, and for the layer-structure carbonaceous slate loaded parallel to the lamina plane it is 0.49. It can be seen that the m of layer-structure carbonaceous slate is different because of the different rock structure and different loading direction, but it is close to 0.45, which is suggested by the standard of the ASTM. Based on this study, the equation $I_{s(50)} = (D_e/50)^{0.44} I_s$ can be used for calculating the corrected PLS of lump-structure carbonaceous slate, and the equation $I_{s(50)} = (D_e/50)^{0.46} I_s$ can be used for calculating the corrected PLS of layer-structure carbonaceous slate in which the loading direction is perpendicular to the lamina plane. The equation $I_{s(50)} = (D_e/50)^{0.49} I_s$ can be used for calculating the corrected PLS of layer-structure carbonaceous slate in which the loading direction is parallel to the lamina plane.

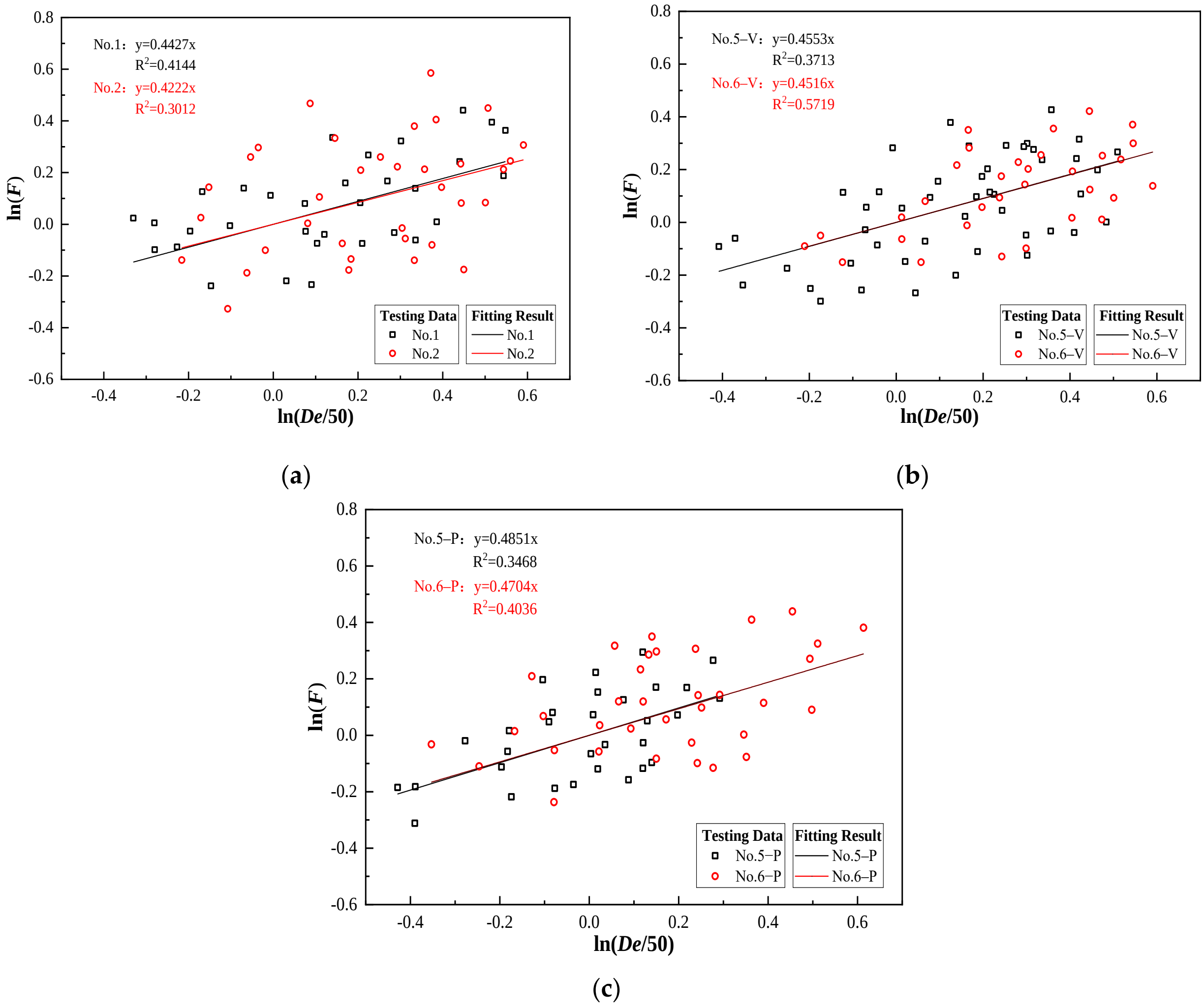


Figure 6. Example of fitting relation curve of ln(F)-ln(D_e/50): (**a**) Lump structure; (**b**) layer structure loaded perpendicular to the lamina plane; (**c**) layer structure loaded parallel to the lamina plane.

3.3. UCS Test Data Statistics Analysis

The calculation method of UCS is shown in Equation (5):

$$\sigma_c = P/A \tag{5}$$

where σ_c is the sample UCS, P is the failure load, and A is the cross-sectional area of the sample.

Different sizes of rock samples will lead to different structural compositions, such as internal microcracks, fissures, and structural planes. Rock samples with different aspect ratios will produce a friction effect at their end. For these two reasons, the failure mode and failure intensity during the UCS testing of rock samples will be different [30,31]. However, according to related scholars' studies, the cubic sample UCS could be transformed into a cylindrical sample by Equation (6) [32], where σ_s is equivalent standard cylindrical sample UCS, is the cubic sample UCS, H is the equivalent cylindrical sample height, and W is the equivalent cylindrical sample diameter.

$$\sigma_s = \sigma_c\left[0.778 + 0.222(h/w)^{-1}\right] \tag{6}$$

Table 3 shows the results of the UCS test. The carbonaceous slate UCS is greatly different, and the test results show that the values range from 1.15 MPa to 23.12 MPa. The lump-structure carbonaceous slate UCS test results range from 1.15 MPa to 5.18 MPa;

this rock is extremely soft. Most carbonaceous slate with typical layer structures has thin- to medium-thickness layers, the rock mass is crushed, and the interlayer is argillaceous cementation. The UCS is substantially affected by layer thickness and lamina plane bonding force. Samples whose loading directions are perpendicular to the lamina plane range from 15.34 MPa to 23.12 MPa, and samples whose loading directions are parallel to the lamina plane range from 6.13 MPa to 17.63 MPa. The anisotropy is significant.

Table 3. Results of uniaxial compressive strength testing.

Location Number	Sample Types	UCS Range (MPa)	Average (MPa)	Cylindrical Sample UCS (MPa)	Standard Deviation	Variation Coefficient (%)
1	Cubic	1.01~1.54	1.30	1.15	0.20	15.1
2	Cubic	1.31~2.17	1.84	1.63	0.26	14.4
3	Cubic	3.33~4.91	4.07	3.62	0.51	12.5
4	Cubic	5.08~6.29	5.82	5.18	0.43	7.5
5-V	Cubic	19.05~24.08	21.67	19.26	1.41	6.5
6-V	Cubic	16.99~20.13	18.28	16.25	0.98	5.4
7-V	Cubic	23.66~29.31	26.00	23.12	2.09	8.0
8-V	Cylindrical	19.13~20.19	20.18	20.18	0.79	3.9
9-V	Cubic	11.87~15.58	13.65	12.13	1.17	8.6
10-V	Cylindrical	14.39~16.62	15.34	15.34	0.80	5.2
5-P	Cubic	11.98~14.19	12.73	11.32	0.78	6.2
6-P	Cubic	12.61~15.37	13.61	12.09	0.86	6.3
7-P	Cubic	18.72~20.92	20.92	17.63	0.68	3.4
8-P	Cylindrical	11.02~13.76	12.18	12.18	0.93	7.7
9-P	Cubic	5.96~7.91	6.90	6.13	0.68	9.8
10-P	Cylindrical	7.15~10.53	9.19	9.19	1.13	12.3

4. Relationship between Corrected PLS and UCS

According to the proposed relationship equations by ISRM and the 'Code for Rock Test of Railway Engineering (China)', the UCS calculated results are generally larger than the UCS test results. Thus, these equations are not applicable for predicting the UCS of carbonaceous slate in the Luang Prabang Suture Zone. For this reason, and based on the PLS test and UCS test results of carbonaceous slate, four types of fitting correlations between PLS and UCS were established that are widely used in related research [32], and fitting equations were obtained as follows:

Zero-intercept linear equation:

$$UCS = 18.45 I_{s(50)} \tag{7}$$

Non-zero-intercept linear equation:

$$UCS = 17.34 I_{s(50)} + 0.9 \tag{8}$$

Power equation:

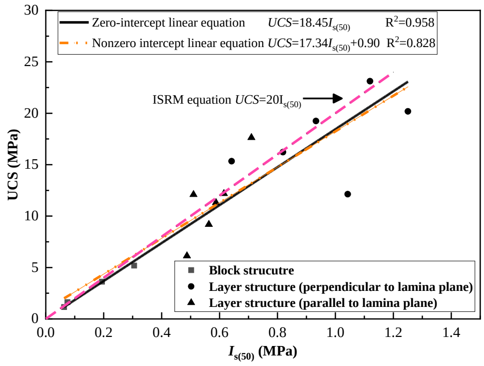
$$UCS = 18.05 I_{s(50)}^{0.849} \tag{9}$$

Logarithmic equation:

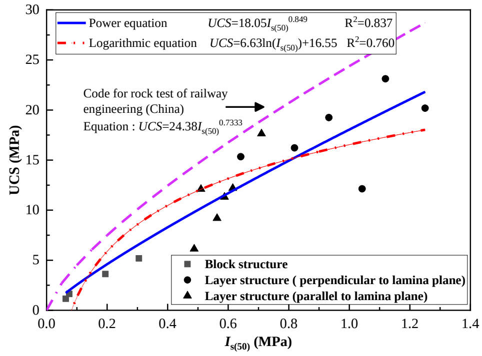
$$UCS = 6.63 \ln\left(I_{s(50)}\right) + 16.55 \tag{10}$$

According to the fitting equations, curves were drawn in Figure 7. Four fitting equations could reflect the relationship between the PLS and UCS of carbonaceous slate, and all determination coefficients are higher than 0.7. The logarithmic equation has the lowest fitting determination coefficient—the value is 0.76. The determination coefficients of the non-zero-intercept linear equation and the power equation are 0.83 and 0.84, respectively. The zero-intercept linear equation has the highest determination coefficient—the value is

0.96. Accordingly, the relationship between PLS and UCS is close to a linear dependence, and it can be expressed as UCS = $18.45I_{s(50)}$, which has higher accuracy in predicting the UCS of the carbonaceous slate in the Luang Prabang Suture Zone.



(**a**) Linear equation



(**b**) Nonlinear equation

Figure 7. Fitting curves of the relationship between UCS and PLS: (**a**) Linear equation; (**b**) nonlinear equation.

5. Discussion

Based on the PLS and UCS test results of the carbonaceous slate in the Luang Prabang Suture Zone, the correction power index m of standard rock samples with different structures and different loading directions was obtained, and the conversion equation between PLS and UCS was proposed. The results of the correction power index m are close to the conclusions of relevant researchers, such as the range from 0.443 to 0.600 proposed by Yin [8], and the 0.45 suggested by the ASTM. However, when the rock structure and loading direction are different, the correction power index m will be anisotropic. For a typical layered rock mass, it is recommended to select an applicable correction power index m for $I_{s(50)}$ estimation. The conversion equation between UCS and PLS proposed in this study is based on the strength test results of carbonaceous slate in the Luang Prabang Suture Zone, so the regional applicability is much stronger. For this reason, follow-up studies should further enhance the verification of carbonaceous slate in different regions.

6. Conclusions

1. Carbonaceous slate is severely influenced by tectonic stress, and the UCS of rocks with different structures is significantly different. The average $I_{s(50)}$ of lump-structure carbonaceous slate is 0.16 MPa, and the UCS ranges from 1.15 MPa to 5.18 MPa. The average $I_{s(50)}$ of layer-structure carbonaceous slate in which the loading direction is perpendicular to the lamina plane is 0.97 MPa, and the UCS ranges from 15.34 MPa to 23.12 MPa. The average $I_{s(50)}$ of layer-structure carbonaceous slate in which the loading direction is parallel to the lamina plane is 0.58 MPa, and the UCS ranges from 6.13 MPa to 17.63 MPa. This means that lump-structure rock is extremely soft, and the anisotropy for layer structure is significant.
2. It was found that the values of the correction power index m are from 0.42 to 0.51 for carbonaceous slate in the Luang Prabang Suture Zone, Laos. These m values are close to the 0.45 suggested by the standard of the ASTM. The $I_{s(50)} = (D_e/50)^{0.44}\ I_s$ can be used for calculating the $I_{s(50)}$ of lump-structure carbonaceous slate, the $I_{s(50)} = (D_e/50)^{0.46}\ I_s$ can be used for calculating the $I_{s(50)}$ of layer-structure carbonaceous slate in which the loading direction is perpendicular to the lamina plane, and the equation $I_{s(50)} = (D_e/50)^{0.49}\ I_s$ can be used for calculating the $I_{s(50)}$ of layer-structure carbonaceous slate in which the loading direction is parallel to the lamina plane.
3. The PLS and UCS of carbonaceous slate in the Luang Prabang Suture Zone are well correlated. The carbonaceous slate UCS prediction results calculated by the ISRM's proposed relationship are substantially larger than the test results. Comparing four

different fitting relationships of the zero-intercept linear equation, non-zero-intercept linear equation, power function equation, and logarithmic equation, the relationship between the UCS and PLS satisfies the zero-intercept linear equation better. It can be expressed as UCS = $18.45I_{s(50)}$ and can be used for geotechnical engineering rock UCS estimation.

4. The relationship between the UCS and PLS of rocks is related to the rock type and geological environment. If the revealed surrounding rock of tunnel engineering is extremely soft, it will be extremely difficult to prepare the standard samples for UCS. For this situation, the PLS can estimate rock UCS effectively.

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