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Impact of disc-cutter partial wear on tunneling parameters and a high-accuracy method for discrimination of partial wear

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Section S1 Experimental Procedure

The experimental procedure is illustrated in Fig. S1. The first step involved adjusting the shield to the correct excavation position. Next, the rock-soil container was filled with the composite strata. The disc were then arranged according to different failure ratios during the assembly process. After these initial steps, full-face excavation mode was selected on the control console, with the cutterhead speed set to 6 r/min and the advance speed set to 6 mm/min.

(a) Test-rig adjustment (b) Rock-soil filling
(c) Cutterhead arrangement (d) Console operation
(e) Shield excavation (f) Completion and exit

Fig. S1 The specific experimental procedure.

Section S2 Time-domain Feature

Table S1 presents a list of specific features of the time domain, including mean, standard deviation, root mean square, square root amplitude, peak-to-peak, skewness, kurtosis, form factor, crest factor, impulse factor, clearance factor, and energy. These features are calculated using their respective formulas (Liu et al., 2021; Qin et al., 2023).

Table S1 Calculation formula for time-domain features

Time domain feature	Calculation formula
Mean	$\bar{s} = \frac{1}{N}\sum_{i=1}^{N} s_i$
Standard deviation (Std)	$\rho_t = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(s_i - \bar{s})^2}$
Root mean square (RMS)	$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} s_i^2}$
Square root amplitude	$S_r = \left(\frac{1}{N}\sum_{i=1}^{N}\sqrt{\lvert s_i \rvert}\right)^2$
Peak-to-peak	$s_{\max} - s_{\min}$
Skewness	$\frac{1}{N}\sum_{i=1}^{N}\frac{(s_i - \bar{s})^3}{\rho_t^3}$
Kurtosis	$\frac{1}{N}\sum_{i=1}^{N}\frac{(s_i - \bar{s})^4}{\rho_t^4}$
Form factor	$RMS \,/ \left(\frac{1}{N}\sum_{i=1}^{N}\lvert s_i \rvert\right)$
Crest factor	$s_{\max} \,/\, RMS$
Impulse factor	$s_{\max} \,/ \left(\frac{1}{N}\sum_{i=1}^{N}\lvert s_i \rvert\right)$
Clearance factor	$s_{\max} \,/\, S_r$
Energy	$\sum_{i=1}^{N} s_i^2$

where s_i is the original sensor signal data, $i = 1, 2, 3, \cdots, N$, N is the number of sampling points, $s_{\max}$ is the maximum value of the signal data, and $s_{\min}$ is the minimum value of the signal data.

Section S3 Frequency-domain Feature

The calculation formulas for frequency-domain features are shown in Table S2.

Table S2 Calculation formula for frequency-domain features

Frequency-domain feature	Calculation formula
Centroid frequency (CF)	$S_1 = \frac{\sum_{k=1}^{N} f_k \cdot P(k)}{\sum_{k=1}^{N} P(k)}$
Average frequency (AF)	$S_2 = \frac{\sum_{k=1}^{N} P(k)}{N}$
Standard deviation of frequency (STDF)	$S_3 = \sqrt{\frac{\sum_{k=1}^{N} (f_k - S_1)^2 \cdot P(k)}{\sum_{k=1}^{N} P(k)}}$
Root mean square frequency (RMSF)	$S_4 = \sqrt{\frac{\sum_{k=1}^{N} f_k^{\,2} \cdot P(k)}{\sum_{k=1}^{N} P(k)}}$

where N represents the number of sample points, $P(k)$ corresponds to the power spectrum value, and f_k represents the magnitude of the frequency value for the corresponding point.

Centroid frequency (CF) refers to the frequency of a signal component that has a significant presence in the spectrum and reflects the distribution of power across the signal's frequency spectrum. Within a specified frequency-band range, the energy contained in the frequency range below the centroid frequency accounts for half of the total signal energy. This concept is derived from the analysis of the signal's power spectrum in the frequency domain, where the centroid frequency represents the central or average frequency of the energy distribution.

The average frequency (AF) represents the arithmetic mean of the power spectrum. This calculation is based on frequency-domain analysis, in which the power spectrum illustrates the distribution of signal power across different frequencies. The average frequency provides a measure of the central tendency or average location of the power spectrum.

The standard deviation of frequency (STDF) indicates the measure of dispersion or variability around the centroid frequency, quantifies the spread or deviation of frequencies, and provides information about the distribution and variability of the power spectrum.

The root mean square frequency (RMSF) is defined as the square root of the mean square frequency. By taking the square root, the root mean square frequency provides a measure of the typical or effective frequency in the power spectrum. It is commonly used to characterize the overall frequency content or distribution of a signal in the frequency domain.

Section S4 Extracted multi-domain features

Table S3 Extracted multi-domain features

Domin	Torque Features	Thrust Features
Time	T_Mean	F_Mean
	T_Std	F_Std
	T_RMS	F_RMS
	T_SquareRootAmplitude	F_SquareRootAmplitude
	T_PeakToPeak	F_PeakToPeak
	T_Skewness	F_Skewness
	T_Kurtosis	F_Kurt
	T_FormFactor	F_FormFactor
	T_CrestFactor	F_CrestFactor
	T_ImpulseFactor	F_ImpulseFactor
	T_ClearanceFactor	F_ClearanceFactor
	T_Energy	F_Energy
Frequency	T_CF	F_CF
	T_AF	F_AF
	T_STDF	F_STDF
	T_RMSF	F_RMSF
Time-frequency	T_SubbandEnergy1	F_SubbandEnergy1
	T_SubbandEnergy2	F_SubbandEnergy2
	T_SubbandEnergy3	F_SubbandEnergy3
	T_SubbandEnergy4	F_SubbandEnergy4