Infrared precursor of pre-cracked coal failure based on critical slowing down

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\textbf{ABSTRACT}

In order to study the precursor information of infrared radiation temperature of coal containing macro-cracks during load bearing damage, infrared monitoring tests of coal instability damage under different crack inclination angles are designed. Based on the critical slowing down theory, the variance and autocorrelation coefficients of the infrared radiation temperature series are calculated to reflect the damage precursors and provide a theoretical basis for early warning of coal and rock dynamic hazards. The results show that the infrared radiation sequences of pre-cracked coals have a critical slowing down effect. The autocorrelation coefficient and the variance of MIRT curve can be more accurate to find the precursor time of instability. In the critical slowing down analysis, the variance is more stable, and the lag step has a great influence on the autocorrelation coefficient. The infrared precursory information of the coal is mostly about 80\% to 85\% of the peak stress or instability time, and the horizontal fracture will make the failure precursory appear in advance.

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\textbf{Introduction}

At present, mine production has gradually entered the stage of deep mining, and safety production will also face greater challenges, especially coal and rock dynamic disasters such as rock burst (Xue et al. 2020), coal and gas outburst (Xu et al. 2006). However, the process of coal and rock mass catastrophe is often accompanied by energy transfer and change (Li et al. 2011; Zou and Jiang 2004), including sound, light, electricity, magnetism and other ways released to the outside world. Then the identification and analysis of these signals will help to master the coal and rock mass disaster information, and have important guiding significance for early-warning coal and rock dynamic disasters and ensuring safe production.

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Infrared remote sensing technology was early applied in earthquake prediction (Geng et al. 1992), and since then, due to the development of infrared thermal imaging technology, this non-destructive detection technology has gradually gained the attention in the field of rock mechanics. Ming (2007) introduced infrared thermal imaging technology to soil dynamics and found plasticity to be one of the most effective heat production mechanisms through experiments. Wu et al. (2002) conducted uniaxial loading on granite, marble and other rocks under the infrared radiation and the infrared radiation variation pattern was obtained based on the average temperature. Liu et al. (2015) entered into fractal, entropy and statistical theories and proposed the use of characteristic roughness and entropy to quantify the evolution characteristics of the infrared radiation temperature field during rock loading. Thereafter Tang et al. (2021) carried out bearing damage tests under infrared monitoring for water-bearing soft coal and obtained the infrared thermal image and infrared radiation variation law of soft coal under different water content. Li et al. (2017) carried out a uniaxial infrared radiation monitoring test on a composite coal sample of rock-coal-rock, and Li et al. (2018) used a self-designed test apparatus to investigate the variation of infrared radiation during the destruction of coal and rock under the action of gas. Cheng et al. (2018) conducted infrared radiation tests on sandstone with prefabricated fractures at different dip angles and found the relationship between infrared radiation variation and fracture angle. Ma et al. (2017) investigated the effect of stress on the intensity and mutation time of infrared radiation during coal rock fracture by uniaxial loading coal samples with different scales. Xue et al. (2021) performed a full-field quantification of deformation and fracturing of flawed rock using digital image correlation A number of experimental studies have been carried out in the field of coal and rock through the use of infrared technology, which proved that infrared radiation can reflect disaster information during the deformation and fracturing of coal and rock, which is of great significance for early warning of disasters using infrared radiation information.

In recent years, the phenomenon of critical slowing down has demonstrated an important potential in revealing whether complex dynamical systems tend to be critically catastrophic (Marten et al. 2009; Gopalakrishnan et al. 2016). This theory can better reflect the precursor information of phase transitions in dynamic systems, Wu et al. (2013) explored the timing of the appearance of precursor signals of sudden climate changes based on this theory. Yan et al. (2011) analysed the critical slowing down phenomenon of the Wenchuan earthquake by observing the radon concentration in water. In addition, relevant studies on coal and rock damage precursors based on this theory were also conducted. For instance, Wei et al. (2018) and Kong et al. (2015; 2017) analysed the critical slowing down characteristics of acoustic emission signals of sandstone and coal, and concluded that the precursor information obtained by the critical slowing down theory is effective in reflecting the rupture of coal and rock. Zhang et al. (2021) investigated the critical slowing down characteristics of acoustic emission signals from gas-bearing coal unloading and compared the factors affecting the critical slowing down characteristics. Shen et al. (2020) analysed the critical slowing down characteristics of the maximum infrared radiation temperature (MIRT) of sandstone at different water contents and found that the higher the moisture content, the more obvious the critical slowing down characteristics.
However, under actual engineering conditions, coal and rock mass are often characterised by macroscopic defects, such as faults, laminations and fractures, so the changes in the bearing process of pre-fractured coal and rocks are more complex. The exploration of precursor information of instability of pre-fractured coal rocks will be more useful for early-warning of coal and rock dynamic hazards. In view of this, infrared monitoring tests under uniaxial compression on coal and rocks with prefabricated macro-cracks at different dip angles based on the critical slowing down theory, are conducted to explore the influence of macroscopic defects on the precursor information of coal and rock damage, and then provide some theoretical support and experimental basis for early-warning of coal and rock dynamic hazards.

**Experimental study**

**Specimen preparation**

The test was carried out on coal from Inner Mongolia, and the same block of intact raw coal was hydraulically cut and processed into rectangular specimens of 50 mm × 50 mm × 100 mm, with an error of not more than 0.02 mm on the end face of the specimens (Xu et al. 2013). A relatively homogeneous sample for macro-crack prefabrication was selected to first drill holes in the center of the specimen side, and then cut the inclination angle with emery wire saw blade. There are 0°, 45°, and 90° macro-cracks, which are divided into three groups, of which the prefabricated cracks are 20 mm long and 2 mm wide. The schematic diagram and parameters of the sample are shown in Figure 1 and Table 1.

**Test system**

The loading system uses RMT-150B electro-hydraulic servo-controlled tester with a maximum vertical output force of 1000 kN, and the deformation loading rate can be controlled at 0.0001~1 mm/s with an accuracy of 3%. The infrared monitoring system adopts Shanghai Thermal Imaging Technology Fotric225s model infrared thermal imaging camera for scientific research, with infrared resolution of 320 × 240, thermal sensitivity of 0.03 °C, corresponding spectral band range of 8~12 μm, the accuracy of measuring temperature can reach ±2% when the ambient temperature is 10~35 °C, and the image acquisition is up to 30 Hz. The test loading system adopts displacement control loading with a loading rate of 0.005 mm/s and the infrared monitoring system

![Figure 1. Sketch of coal specimen.](image)
at a frequency of 20 Hz/s. To reduce the effect of end effects, a lubricant is applied between the specimen and the indenter prior to loading. To ensure the reliability of the infrared thermographic observations, test observations were carried out with reference to the relevant test measures (Tang et al. 2021). And the test system is shown in Figure 2.

Infrared radiation characteristics of pre-fractured coal damage

Indexes for infrared radiation analysis

Through the test, the original infrared thermal image of the whole damage process of the sample is obtained. The original infrared thermal image of the typical sample is shown in Figure 3. It can be seen from Figure 3 that the infrared radiation change of the prefabricated crack during the instability process is obvious, and it is necessary to further process and analyze the infrared radiation characteristics of coal during the damage process.

Based on previous studies, the analysis of data in infrared thermal images mainly includes AIRT (Average infrared radiation temperature), MIRT (Maximum infrared radiation temperature), VIRT (Variance of infrared radiation temperature) and VDIIT (Variance of differential infrared image temperature). The above analysis methods have obvious effect in infrared monitoring of coal and rock fracture.

AIRT is the mean value of all infrared radiation intensities in each frame of the infrared thermal image video, which can directly reflect the overall change of the sample temperature field. The average infrared radiation temperature of frame \( p \) is:

\[
\text{Ave}(p) = \frac{1}{L_x \cdot L_y} \sum_{x=1}^{L_x} \sum_{y=1}^{L_y} f_p(x, y)
\]

where \( L_x \) is the maximum row of the infrared radiation matrix; \( L_y \) is the maximum column of the infrared radiation matrix; \( f_p(x, y) \) is the infrared radiation matrix.

MIRT is the maximum value of infrared radiation intensity in each frame of infrared thermal image video, which can intuitively reflect the sudden change of temperature of the sample during the loading process. The greater the MIRT, the more intense the sudden change. The maximum infrared radiation temperature of frame \( p \) is:
Max\( (p) = \max\left( \frac{1}{L_x \times L_y} \sum_{x=1}^{L_x} \sum_{y=1}^{L_y} f_p(x, y) \right) \) 

VIRT is the infrared radiation variance of each frame in the sample infrared thermal image video (Ma et al. 2016). It can describe the differentiation of the sample temperature field and reflect the degree of deviation of the temperature field from the mean value. The more pronounced the divergence, the greater the variance. The infrared radiation temperature variance of frame \( p \) is:

\[
\text{Var}(p) = \frac{1}{L_x \times L_y} \sum_{x=1}^{L_x} \sum_{y=1}^{L_y} [f_p(x, y) - \text{Ave}(p)]^2
\]

The physical meaning of VDIIT can reflect the discreteness of the surface IR temperature values of a sample in the successive difference infrared image. VDIIT can be obtained by calculating the temperature matrix variance of successive differential sequence IR (Ma et al. 2019). The IR temperature matrix variance of frame \( p \) of the successive differential sequence IR chart is defined as follows:

\[
\phi_p(x, y) = f_{p+1}(x, y) - f_p(x, y)
\]

\[
\text{Ave}'(p) = \frac{1}{L_x \times L_y} \sum_{x=1}^{L_x} \sum_{y=1}^{L_y} \phi_p(x, y)
\]

\[
\text{VDIIT}(p) = \frac{1}{L_x \times L_y} \sum_{x=1}^{L_x} \sum_{y=1}^{L_y} [\phi_p(x, y) - \text{Ave}'(p)]^2
\]
Taking the results of NY-45-1 as an example, the above indicators are extracted and compared, as shown in Figure 4. Among them, AIRT is the index obtained by averaging the infrared temperature matrix, which can reflect the change of infrared radiation on the surface of the coal as a whole, but the coal damage process is complex, and the superposition of the warming and cooling effect may lead to its small change in amplitude and it’s difficult to observe the small change. For MIRT, it can reflect the sudden change of high temperature during the bearing damage of the specimen, and through comparison, MIRT is found to be more regular than AIRT, which is more conducive to the identification of infrared radiation information. The temperature change of the specimen will cause its own temperature distribution to

Figure 3. Original infrared thermography.

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change, while VIRT starts from the whole of the infrared thermal image to discern the change of its surface infrared radiation distribution, which is more relevant for the description of the infrared thermal image. VDIIT is the variance of the difference matrix of the thermal image, reflecting the dispersion of the infrared radiation, and has a similar trend to MIRT and VIRT, which also reflects the infrared radiation of the specimen.

**Infrared radiation characteristics of pre-fractured coal**

Through the above comparison, it can be found that AIRT can reflect the overall temperature change trend of the coal in the expression of the infrared radiation of the sample, but its small change range is not conducive to observation. MIRT has a large change range and has a good corresponding effect with the load change of the sample, while VIRT and VDIIT can more sensitively reflect the change of the infrared radiation, but its calculation process is complex, and the data processing efficiency needs to be improved. Therefore, for the subsequent critical slowing down analysis, the MIRT was mainly carried out. The stress-strain and MIRT-time curves of the pre-cracked coal were obtained for the first group of specimens as shown in Figure 5.

The load-bearing damage process of pre-fractured coal is broadly divided into four stages: the compaction stage, the elastic deformation stage, the plastic deformation
stage and the post-peak stage (Zhou et al. 2022; Zhu et al. 2022). The mechanisms affecting changes in the infrared radiation of the coal include the elastic-plastic deformation of the coal, the friction accompanying the rupture of the coal, the effects of tensile damage to the coal and the desorption and diffusion of gases within the coal, the first two of which are primarily responsible for the increase in infrared radiation and the latter two for the decrease in infrared radiation (Chen et al. 2009; Li et al. 2018). As a porous medium, the compacting stage (I) is mainly the densification of the primary pore fractures within the coal. The influence on the infrared radiation temperature at this point is mainly due to the diffusive escape of gases present within

Figure 5. Stress-strain and MIRT-time curves.
the coal and the small amount of coal particle friction in the deformation, so there is no rise and fall fluctuation in the infrared radiation on the surface of the coal at this stage, although there is some undulation. This is followed by the linear elastic phase (II), during which the coal rock gradually accumulates elastic potential energy due to external loading, during which the IR radiation tends to rise gradually, as shown in NY-45-1 and NY-90-1, but changes more steadily. NY-0-1, on the other hand, shows more obvious damage at the precast fractures during the elastic stage, resulting in more obvious fluctuations in the rise and fall of the infrared radiation right at that stage. Until the plastic deformation stage (III), the specimen in this stage of the damage can’t be recovered, at this time the infrared radiation curve changes are also more obvious, both sudden changes in the case of Figure 3(b), there will be obvious rise and fall fluctuations as Figure 3(c). Finally the stress peak is reached in the post-peak phase (IV), where the specimen destabalises and ruptures and the surface infrared radiation spikes. The infrared radiation curve reflects the changes in surface infrared radiation during the bearing to destabilisation process, where the infrared radiation surge corresponds to the destabalisation of the coal rock, while the rise and fall fluctuations and the increase in the infrared radiation have some ability to characterise the plastic damage of the coal rock, which is of positive significance in finding the precursor information for the early warning of the pre-fractured coal rock dynamic disaster.

**Critical slowing down analysis of infrared radiation from pre-fractured coal**

**Theory of critical slowing down**

Critical slowing down is a concept in statistical physics, when a dynamic system from one phase state to another before the transition occurs, the system tends to near the critical point, especially on the critical point, will be conducive to the formation of the new phase state of the dispersion of the rise and fall phenomenon. This dispersion rise and fall is not only manifested in the increase in the amplitude of the rise and fall, but also manifests itself in the lengthening of the duration of the rise and fall, the recovery rate of the disturbance becomes slower and the ability to recover to the old phase state becomes smaller. This lengthening of the duration, the slower recovery rate and the reduced ability to recover are the manifestations of critical slowing down (Marten et al. 2009).

During the bearing process of the coal containing prefabricated cracks, the initial specimen is the initial phase state and the final destabilised damaged specimen is the other phase state. As the load on the coal increases over time, this results in the initial phase state accumulating elastic potential energy as it transitions to the final unstable phase state. The accumulation of elastic potential energy also leads to damage to the coal during this period, which is more pronounced in coal containing prefabricated cracks. Infrared radiometric tests of the coal can therefore be used to reflect the dynamical catastrophe process from an infrared perspective and thus provide early warning of related dynamical hazards. The variance and autocorrelation...
coefficients of the time series in a dynamic system have been found to reflect the phase transition of the dynamic system.

Where variance is a characteristic quantity describing the extent to which the data in the sample deviate from the mean $\bar{x}$, denoted as $s^2$:

$$s^2 = \frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2$$  \hspace{1cm} (7)

where, $x_i$ is the $i$th data; $n$ represents the number of samples.

The autocorrelation coefficient is a variable that describes the correlation between different moments of the same variable, and the autocorrelation coefficient function with variable $x$ lagged by a certain length $j$ is denoted as $\alpha(j)$:

$$\alpha(j) = \sum_{i=1}^{n-j} \left( \frac{x_i - \bar{x}}{s} \right) \left( \frac{x_{i+j} - \bar{x}}{s} \right)$$  \hspace{1cm} (8)

We assume that there is a repeated disturbance of the state variable after each period $\Delta t$. Between disturbances, the return to equilibrium is approximately exponential with a certain recovery speed, $\lambda$. In a simple autoregressive model this can be described as follows:

$$x_{n+1} = e^{\lambda \Delta t} x_n + s e_{n+1}$$  \hspace{1cm} (9)

where $x_n$ is the deviation from the state variable of the dynamic system to the equilibrium state; $e_n$ is the random quantity conforming to normal distribution; $s$ is the mean square deviation. If $\lambda$ and $\Delta t$ don’t depend on $x_n$, then Equation (9) can be simplified as:

$$x_{n+1} = \alpha x_n + s e_{n+1}$$  \hspace{1cm} (10)

where $\alpha$ is the autocorrelation coefficient, $\alpha = e^{\lambda \Delta t}$.

The autoregression of Equation (10) is analyzed by variance, that is:

$$\text{Var}(x_{n+1}) = E(x_n^2) + (E(x_n))^2 = \frac{s^2}{1 - \alpha^2}$$  \hspace{1cm} (11)

In the process of approaching the critical point, the recovery rate of small-scale perturbations will gradually become slower, and when the system approaches the critical point, the recovery rate $\lambda$ will approach zero, while the autocorrelation coefficient $\alpha$ will approach 1, and the variance will tend to be infinite at this time. The increase in variance and autocorrelation coefficient can therefore be taken as a precursor to the system approaching the critical point (Shen et al. 2020).
Influence of window length and lag length

The analysis of precursor information from pre-fractured coal infrared radiation based on critical slowing down is investigated in this paper by means of two metrics, the autocorrelation coefficient and the variance. Before calculating these two metrics, the window length and lag step need to be determined. As shown in Figure 6, the window length refers to the basic unit for performing sequence analysis, and the lag step represents the length of the delay performed after the selected window sequence to another new sequence (Zhang et al. 2019). The variance is the variance of the new sequence obtained by lagging the selected window length by a fixed step, while the autocorrelation coefficient is the correlation between the selected window sequence and the new sequence obtained by lagging a fixed step. Since the variance of the window length and lag step is related to the stability of the autocorrelation coefficient, the infrared sequences of pre-fractured coal were first analysed for the one-way effects of both. First, fix the lag step to 40 and take different window lengths of 200, 400, 600. After that, the fixed window length is 400, and the different lag steps are 40, 100, 200. The effects of different lag steps and window length on autocorrelation coefficient and variance are compared. On this basis, the NY-0-1 specimen with a crack inclination of 0° was used as an example for investigation.

From Figure 7(a) and (b), it can be found that when the lag step is certain, for the variance, the window length affects the magnitude of its curve change, in addition, as the window length increases, a small amount of lag appears in the precursor of the sudden change of the curve, but the final sudden change time nodes basically overlap, and the overall change trend is more stable. The autocorrelation coefficient, on the other hand, is basically similar to the effect of the variance due to the length of the window. In general, the smaller the window length, the more carefully the variance and autocorrelation curves are plotted, and the earlier the mutation point appears; the larger the window length, the flatter the variance and autocorrelation curves.

It can be found from Figure 7(c) and (d) that when the window length is constant, the trend of variance curve under different lag steps is basically the same, there is little difference in value, and the time node of curve change is almost the same. The autocorrelation coefficient has great changes. Due to the different lag steps, the autocorrelation coefficient has the opposite trend. This is because with the increase of lag step, the calculation window continues to delay, the data including the previous window gradually decreases, and its autocorrelation tends to weaken. Although when the lag step is large, the mutation of autocorrelation coefficient changes from positive
Figure 7. Comparison of critical slowing of different window lengths and lag steps.
Figure 8. Critical slowing down characteristics of infrared radiation of specimens with different inclination angles.
correlation to negative correlation, the time node of its change is closer, and the lag step grows a little earlier.

Based on the above analysis and comparison, the choice of lag step and window length has an impact on the processing of the infrared radiation data series, which is consistent with the analysis results of Kong et al. (2015, 2017) and Shen et al. (2020). For the window length, a smaller window length can be chosen, as the precursors of mutations can appear earlier in this case, and the curve can be more detailed. For the lag step, it is not advisable to choose too large, although a large lag step can make the sudden change point appear earlier, but it will make the curve trend change more unfavourable to the analysis. Therefore, it is necessary to make several selections within the window to choose the right lag length for the analysis. In general, the variance is more sensitive to the emergence of mutations and better reflects the moment when they occur, while the autocorrelation coefficient amplifies small changes in the series to facilitate analysis.

Infrared precursor analysis of pre-fractured coal

Based on the above analysis, the effect of window length and lag step is considered, so the section chooses a window length of 200, (i.e. 10 s for a set of data) and a lag step of 40, (i.e. 2 s lag) for the data processing of the infrared radiation time series obtained from the experiment, as shown in Figure 8. A comparison of the IR radiation change curves of the specimens shows that sudden changes in the variance and autocorrelation coefficients usually occur at fluctuations in the IR radiation curve, especially at surges in infrared radiation. The variance and autocorrelation coefficients were found to be stable when the infrared radiation curve was smooth and without significant fluctuations. Based on the critical slowdown theory, the sudden change in variance and autocorrelation coefficients can reflect the precursor of phase transition in pre-cracked coal samples (Kong et al. 2017).

The calculation and analysis of the critical slowing down index revealed that the sudden increase in the variance and autocorrelation coefficient not only reflected the surge in MIRT, but also had a strong sensitivity to its fluctuation. For example, the MIRT of specimen NY-0-1 shows no dramatic changes during the test as a whole and only a sudden change in temperature at the final rupture, but the variance and autocorrelation coefficients reflect the fluctuations in the MIRT in the medium term and the sudden increase in temperature at the end. Based on the theory of critical slowing down, it is known that similar rise and fall fluctuations are precursors to phase transitions and can thus be used as a signal to warn of associated catastrophes. This provides new early-warning information compared to the use of observed temperature surges alone.

It can be seen from Figure 8 that the NY-0-1 specimen showed damage precursor information at around 290 s, corresponding to a stress intensity of 5.64 MPa, which was 52.81% of the peak stress and 65.91% of the moment of damage in time; the NY-45-1 specimen showed damage precursor information at around 262 s, corresponding to a stress intensity of 14.47 MPa, which was 81.33% of the peak stress and 78.92% of the time at the moment of damage; NY-90-1 specimen showed the damage precursor
information at around 370 s, corresponding to a stress intensity of 23.36 MPa, which is 85.10% of the peak stress and 86.45% of the time at the moment of damage. The damage precursors of the specimens advance as the pre-cracking inclination of the specimens decreases, but overall they all start from the plastic phase. Among $\alpha$ The proportion of stress and time before failure of 90° specimen is close, the difference of 45° specimen is small, and the difference of 0° specimen is large. Because when the crack inclination angle is 0°, the strength of the sample decreases, and the sample has plastic damage at the prefabricated crack earlier. Because the crack is horizontal, the plastic damage mainly leads to the complete closure of the sample crack, and then the sample continues to enter the bearing state. And this process results in two phases of approximate elastic deformation of the specimen and at the same time complicates the variation of the infrared radiation on the surface of the specimen, causing an oscillation in the mid-MIRT. However, as the pre-crack inclination increases the strength of the specimen increases and the specimen becomes more stable during the linear elastic phase, but the subsequent damage to the specimen during the plastic deformation phase will not allow the specimen to continue to carry the load for a longer period of time. This results in a relatively steady increase in its MIRT in the early stages and a surge in temperature during plastic breakdown. Therefore, when the crack inclination becomes larger, the damage precursors are more likely to occur near the beginning of the plastic phase.

According to the data processing results, the precursory information of each sample based on the critical slowing down characteristics is obtained, as shown in Figure 9. The peak strength of the sample increases with the increase of crack inclination, which is similar to the previous experimental results (Li et al. 2017). In addition, it can be found that the nodes of infrared precursors in the process of bearing and failure of the sample are obviously delayed with the increase of the crack inclination, mostly about 80%~85% of the stress peak and instability time, which corresponds to the plastic stage of the sample in the stress-strain curve. The plastic deformation is the main reason for the temperature change of the coal, and the plastic deformation
of the coal is gradually delayed due to the increase of the crack dip angle. It can be seen that the infrared radiation information based on the critical moderation theory can effectively reflect the precursory information of instability and failure of pre-cracked coal and rock.

Conclusions

(1) Among AIRT, MIRT, VIRT and VDIIT, AIRT has a more general effect, MIRT better reflects the instability of the coal, VIRT and VDIIT are more sensitive but complicated to calculate.

(2) Based on the critical slowing down theory, the sudden increase of variance and autocorrelation coefficient of infrared radiation MIRT sequence corresponds to its sudden increase and fluctuation, which can effectively obtain the precursor information of coal instability.

(3) The variance and autocorrelation coefficients of the infrared radiation series are affected to some extent by different window lengths and lag steps, with the variance being less affected overall and the autocorrelation coefficient being more affected by the lag step.

(4) When the dip angle of pre-cracked coal is 45° and 90°, the infrared radiation precursor of its near failure is about the initial stage of plastic deformation, while when the dip angle is 0°, the precursor will appear in advance. In combination with thermal imaging this will provide effective information for early-warning of kinetic catastrophes in fractured coal.

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Data availability statement

The data that support the findings of this study are openly available in [repository name] at [URL], reference number [reference number].

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