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Experimental study on the change features of infrasonic waves in coal sample loading

In order to study the change features of infrasonic waves in coal sample loading, we collect coal samples from the research area, conduct both lab test and theoretic analysis, and based on filtered and de-noised signals, establish the characteristic parameter of infrasonic waves – relative energy, and analyze the changes in the energy parameter of infrasonic waves in the loading process. The analysis shows: in the loading process, the energy of infrasonic waves changes in stages, including the slow increase, rapid increase towards the peak and slow decrease stages, which are consistent with the deformation stages of coal samples, and when the coal samples enter the plastic deformation stage from the elastic deformation stage, the infrasonic waves show an obvious abnormal change. Therefore, we can predict the deformation and failures of coal samples according to the changes in the energy of infrasonic waves. At the same time, due to advantages like non-coupled contact and small attenuation, the infrasonic wave prediction method is very useful in the coal sample failure prediction. This is of great significance to improving the accuracy of coal sample failure prediction and reducing coal mine accidents.

Keywords: *Infrasonic waves, relative energy, prediction of coal sample failures, precursor characteristics, analytical method.*

1. Introduction

Prediction of coal sample failures is the foundation for predicting the geological hazards for coal mines. In order to achieve accurate prediction of coal mine accidents, researchers have carried out a number of studies. In the research on the failures of coal samples, the internal structures of these samples are hard to directly observe. Therefore, a number of researchers started with the attendant phenomena of coal sample deformation and failures and have gradually developed a series of prediction methods like the acoustic emission prediction technology, electromagnetic radiation prediction technology, microseismic prediction technology and ultrasonic prediction technology[1-9]. With more researches being carried out, these prediction methods have been continuously modified, achieving higher prediction accuracy and better results in the practical application. However, these prediction method also have their shortcomings, such as coupled contact, fast attenuation and large interference, which are more prominent under some special test conditions, especially in the complex underground conditions of coal mines, seriously limiting their applicability. Therefore, through analysis on the shortcomings of the existing prediction methods, some researchers proposed predicting the deformation and failures of coal samples according to the change patterns of low-frequency infrasonic waves[10].

Infrasonic waves are sound waves with a frequency of 0.01~20Hz. This kind of sound wave has a low frequency and a long wavelength and can easily diffract during propagation, so it has such merits as small attenuation and long propagation distance [11-12]. Due to the various advantages, infrasonic wave is widely applied in many fields, such as gene induction, lesion therapy, boiler deslagging, infrasonic wave weapons, pipeline leak monitoring, etc.[13-17], especially in the prediction of natural disasters like earthquakes, tsunamis, landslides and volcanic eruptions[18-19], and mature application technologies have been developed. Whether a natural disaster like an earthquake or landslide, or an underground geological hazard in a coal mine is a process where a coal-rock mass deforms, fails or becomes unstable. Therefore, some researchers have carried out both laboratory tests and theoretical analysis to demonstrate the feasibility of infrasonic wave prediction technology and prove it is feasible to predict coal sample failures according to the change features of infrasonic waves[10]. In order to further analyze how infrasonic waves respond to the deformation of coal samples, some researchers have analyzed the change features of infrasonic waves in the loading process of rock samples with different lithologies and studied the effects of lithology on the response features of infrasonic waves[20]. Some researchers have also studied the energy ratio of infrasonic waves in different frequency bands in the loading process and analyzed the relative change patterns of the

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energy of infrasonic waves in the high and low frequency bands with the loading[21]. Some researchers have carried out a lot of research on the change features of infrasonic waves in the coal-rock sample loading process and achieved fruitful results. Understanding the change patterns of infrasonic waves in different loading stages, especially the response features of infrasonic waves before any failure, is of great significance to the study on the prediction of coal rock deformation and failures. However, so far, no research has been reported on the change patterns of infrasonic waves in different loading stages, especially the response features of infrasonic waves before any failure. Therefore, in this paper, we collect coal samples from the research area, conduct test on the response features of infrasonic waves in the loading process, establish a relationship between the coal sample deformation and the response of infrasonic waves, especially the response features of infrasonic waves before the coal samples failure, and then predict the deformation and failures of coal samples according to the changes in infrasonic waves for the purpose of improving the prediction accuracy and providing guidance to the development of infrasonic wave prediction methods for geological hazards in coal mines.

2. Experimental scheme

2.1 Experimental apparatuses

The experimental apparatuses include the coal rock stress loading device developed independently by Henan Polytechnic University and the CASI-ISM-2013 high-precision capacitance infrasonic wave acquisition system developed by Chinese Academy of Sciences. This device mainly consists of an axial compression loading system, a stress-strain acquisition system and an infrasonic wave acquisition/analysis system. The experimental principle is shown in Fig.1.

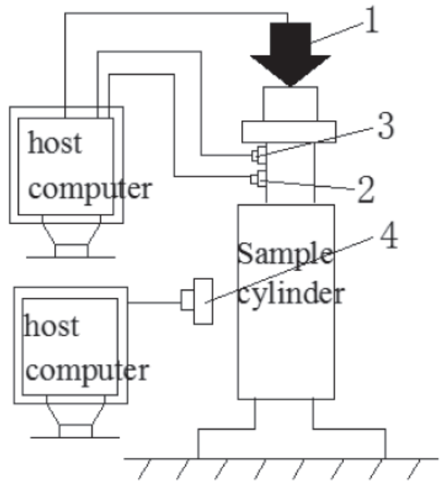

Fig.1 Schematic diagram of experimental apparatus

(1) Stress loading system

The stress loading system is controlled by an all-digital computer program and provides automatic storage and display of the parameters acquired. It has such advantages as high resolution, high control precision and low failure rate, which ensure the reliability of the experimental data. The axial stress loading system has a stress loading range of 1kN~500kN; the stress transducer is mainly used to monitor the axial stress, with a monitoring range of 0~500kN and a test force resolution of <2.5N; the displacement transducer is mainly used to monitor the axial displacement, with a monitoring range of 0~150mm and a displacement measurement resolution of <0.002mm.

(2) Infrasonic wave acquisition system

The infrasonic wave acquisition system converts the non-electrical signals into electrical signals through the infrasonic wave transducer. Through the pre-amplifier, the signals are transmitted to the digital network transmission acquisition apparatus for storage. The working principle of the transducer is shown in Fig.2. The acoustic compliance of diaphragm and the plate electrode compose a capacitor. Affected by the infrasonic waves outside, the metallic diaphragm produces vibration, changing the distance d between the plates, which further leads to changes in the capacitance of the plane-parallel capacitor. The changes in capacitance achieves the conversion from non-electrical signals to electrical signals, reflecting information on infrasonic waves through measurement. According to the basic principle of a capacitor, the capacitance calculation formula is as follows:

$$C=\frac{\varepsilon S}{4\pi kd} \quad \ldots \quad (1)$$

where: ε - dielectric constant; S - enfilade area of the parallel plates; k - electrostatic constant; d - distance between plates. When the distance d changes by Δd, the change in capacitance is:

$$\Delta C=\frac{\varepsilon S}{4\pi k(d-\Delta d)}-\frac{\varepsilon S}{4\pi kd}=C_0\frac{\Delta d}{d-\Delta d} \quad \ldots \quad (2)$$

where: C_0 - initial capacitance when the distance between plates is d.

This transducer has a sensitivity of 328mv/Pa and a measurable frequency scope of 0.001Hz~100Hz. The network transmission device adopts the 16-bit arithmetic, with a sampling rate set within a range of 0.1Hz~250kHz and a quantization error of ±0.003%.

2.2 Preparation of coal samples

The research area is located in the mining area in Jincheng. We mainly collect low-medium grey and high-strength anthracite from coal bed 3# from Shanxi Formation. According to the coal collection and preparation requirements, we collect coal samples from a fresh coal wall and seal them for preservation. At lab, we prepare them into standard sample

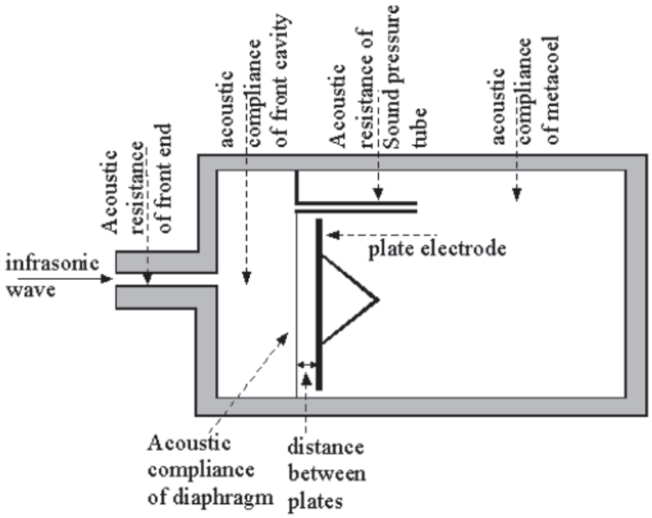

Fig.2 Work principle diagram of CASI-ISM-2013 infrasound sensor

columns with a diameter of 50mm and a length of 100mm along the axial direction perpendicular to the bedding. The upper and lower surfaces of the samples should have flatness that meets the rock mechanics testing requirements. We then seal the coal samples prepared for later use. There are 8 coal samples, of which 2 are spare ones.

2.3 Experimental principle and test procedures

In the uniaxial loading process, due to the weak surfaces inside the coal samples and the uneven load, when the bearing capacity of a local area is less than the load, a failure will occur in this local area, and then produce infrasonic waves with different frequencies and amplitudes. The differences in the features of infrasonic waves are determined by the differences in the internal deformation features of the coal samples and are the external representation of the internal evolution of the coal samples. Therefore, we analyze and try to establish the relationship between the internal deformation of coal samples and the response of infrasonic waves so that we can conduct inversion analysis and predict the internal deformation of coal samples according to the features of infrasonic waves.

When acquiring signals, in order to test the feasibility of uncoupled acquisition of infrasonic waves, the infrasonic wave transducer adopts the uncoupled mode, which is located 40cm away from the coal sample.

The specific steps of the test are as follows:

A Put the sample into a sample cylinder, and fix the infrasonic wave transducer;

B Set infrasonic wave acquisition parameters and conduct ambient noise test. When the ambient noise is stable, go to the next step; when the ambient noise fluctuates abnormally, conduct the test at some other time if possible;

C Set stress loading parameters, use the load control mode, and set the loading speed to 200N/s. At the same time, set the acquisition parameters of infrasonic waves;

D At the same time, activate the stress loading device and infrasonic wave acquisition device and start testing;

E Keep loading until the coal sample fails. Record and save the parameters in the loading process.

3. Analytical methods

3.1 Filtering and de-noising

The purpose of filtering is to filter the test signals and leave the acoustic signals in the desired frequency band. By setting the passband frequency, stopband frequency, passband attenuation and stopband attenuation, we design the Butterworth filter. Ideally, the filter has a coefficient of 1 in the passband and 0 in the stopband. We set the filter passband to 0.01-20Hz, to achieve signal filtering.

The purpose of de-noising is to remove the noise interference in the test signals, which is accomplished by wavelet decomposition and threshold denoising in this paper. Based on the wavelet decomposition of test signals, we obtain the threshold by the Stein's unbiased risk estimate method to and conduct thresholding of the high frequency part by the soft threshold method, and then reconstruct the processed wavelets.

3.2 Relative energy of infrasonic waves

The relative energy of infrasonic waves represents the intensity of the infrasonic wave event. It is one of the important parameters that characterize the variation features of infrasonic waves. The infrasonic wave transducer mainly test the variation of the amplitude over time, and the amplitude represents the magnitude of signal vibration, which, to some extent, can represent the signal energy. Therefore, by reference to the previous research on energy, relative energy can be expressed as:

$$E=\int \left| f(t) \right|^2 dt \qquad \text{...} \qquad (3)$$

where: E - relative energy, 1; $f(t)$ - sound wave amplitude function; t - time.

The infrasonic wave transducer records a discrete time series, so the relative energy over a period can be expressed as:

$$E_0=\sum_M^N \left| f(t_i) \right|^2 \frac{1}{F} \qquad \text{...} \qquad (4)$$

where: E_0 - accumulated relative energy of infrasonic waves from the time M/F to N/F, 1; $f(t_i)$ - the sound wave amplitude corresponding to the i-th sampling point; M, N - number of M and N, respectively; F - sampling frequency, Hz.

According to Formula (4), we can deduce that, over a period, the relative energy of infrasonic waves in a certain frequency band can be expressed as:

$$E_1=\sum_M^N \left| g(t_i) \right|^2 \frac{1}{F} \qquad \text{...} \qquad (5)$$

where: E_1 - relative energy of infrasonic waves in a certain frequency band over a certain period, 1; $g(t_i)$ - sound wave amplitude of $f(t_i)$ corresponding to the i-th sampling point after being passband filtered.

4. Result analysis and discussion

After analyzing the test samples, we find that for different coal samples, the overall change patterns of infrasonic waves are similar and the mechanisms are the same. In order to avoid repeated demonstration, we select the first two coal samples - 1# and 2# for detailed discussion.

4.1 Test results of ambient noise

In order to avoid the influence of abrupt signals in the test environment on the test results, we should conduct the test when the ambient noise becomes relatively stable. Before the test, we test the ambient noise. The time-frequency analysis result is shown in Fig.3.

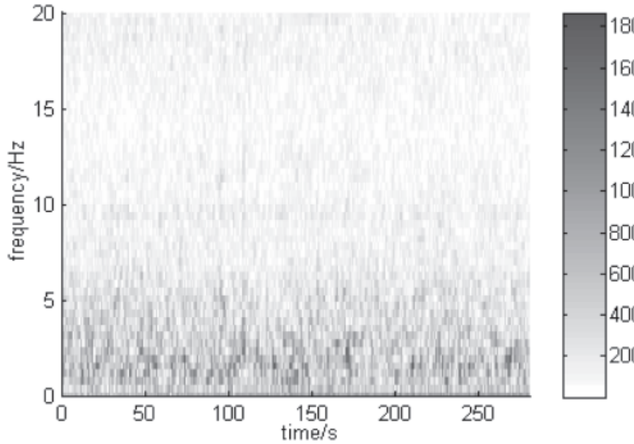

Fig.3 Test results of ambient noise
(the grayscale represents the intensity)

From the test results, it can be seen that: the ambient noise is relatively stable in terms of frequency and amplitude, and there are few abnormal fluctuation signals in the noise signals, so the environment is suitable for the test on the infrasonic wave signals of coal sample deformation.

4.2 Test results of stress-strain

According to the experimental design, we conduct a test on the coal samples for the infrasonic waves in the uniaxial loading process. In order to facilitate the analysis on the relationship between infrasonic waves and coal sample deformation, we draw the stress-strain-time curves for the coal samples, as shown in Fig.4.

As can be seen from the stress-strain curves of coal samples, the stress-strain of the coal samples during the loading process change in stages, which include the compression, elastic deformation, plastic deformation and post-peak failure stages. Since our analysis focuses on the variation features of coal samples before any failure, we divide

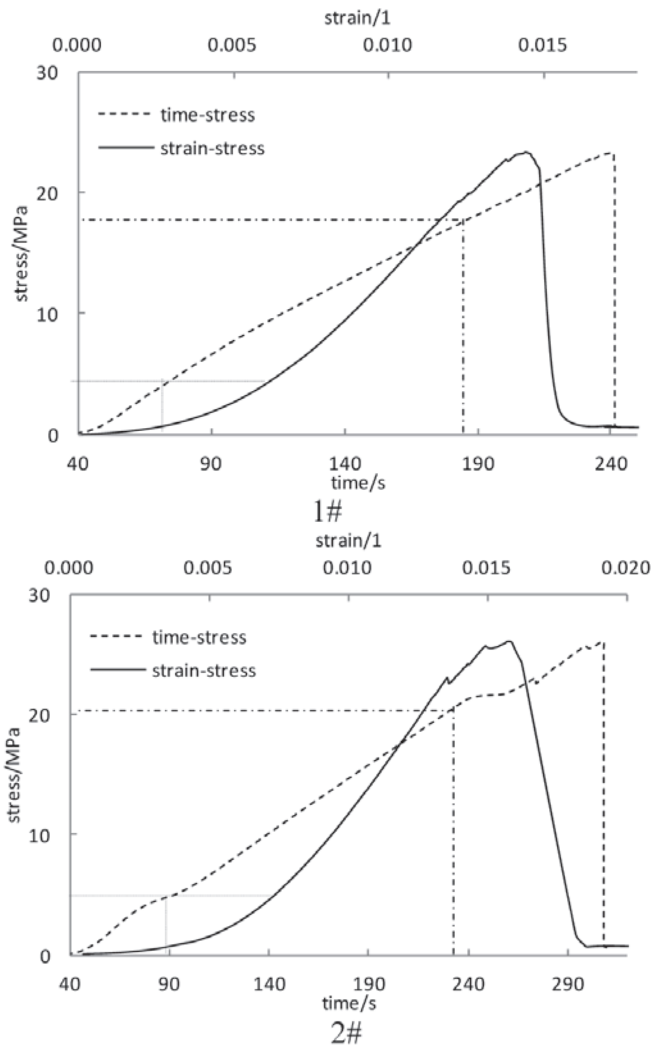

Fig.4 Stress-strain-time graphs of coal samples

the stress-strain variation relationship into compression, elastic deformation, elastic and subsequent deformation stages. For coal sample 1#, the stress reaches 4.5Mpa after loading for 70s, and it reaches 17.5Mpa, which is the yield limit after 180s and the coal sample changes from elastic deformation to plastic deformation. For coal sample 2#, the stress reaches 5Mpa after 90s of loading and the coal sample changes from compression to elastic deformation, and after 230s of loading, the stress reaches 20.5Mpa, which is the yield limit, and the coal sample changes from elastic deformation to plastic deformation.

4.3 Test results of infrasonic wave energy

According to the experimental design, we conduct a test on the infrasonic waves in the uniaxial loading process. In order to prevent the energy features of the infrasonic waves in different frequency bands from being covered up, we divide the whole low frequency band (0.01-20Hz) into four bands - 0.01-5Hz, 5-10Hz, 10-15Hz, 15-20Hz. According to the calculation method for relative energy of infrasonic waves, we calculate the energy of infrasonic waves in different frequeny bands at an interval of 5s, and sum up the results of the four bands. In this way, we obtain the relative energy of infrasonic waves in the whole low frequency band, and draw the curves with the loading time, as shown in Fig.5.

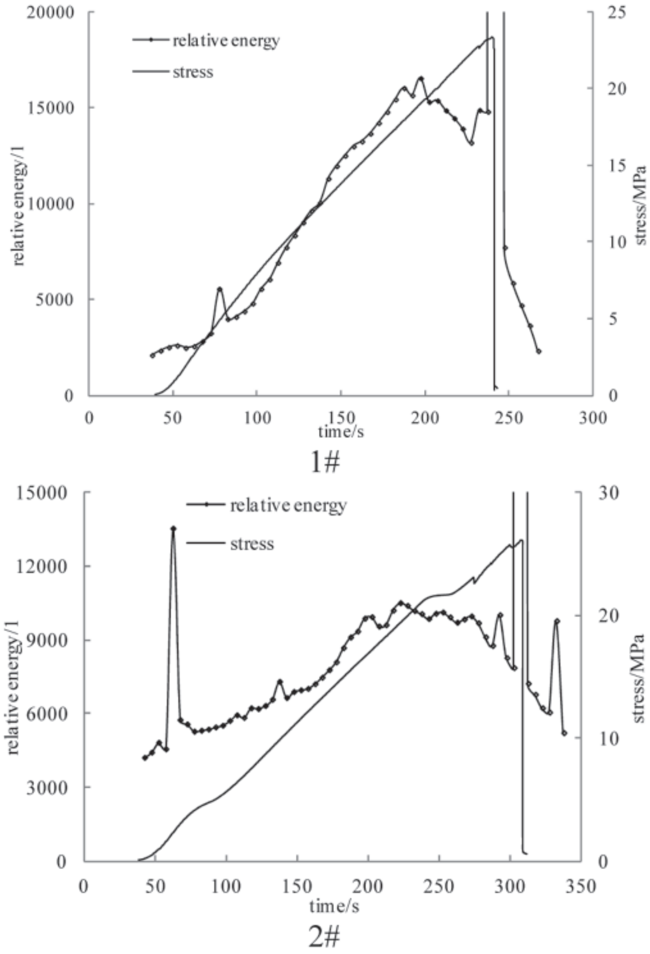

Fig.5 Variation diagrams for relative energy of infrasonic waves over the loading time

From the change patterns of the relative energy of infrasonic waves with the loading time, it can be seen that: the relative energy of infrasonic waves changes in stages in the loading process. The specific changes are as follows:

For coal sample 1#, before loading to 70s, the relative energy of infrasonic waves increases slowly. This stage corresponds to the compression in the deformation of the coal sample, which is dominated by the closing of pores and fissures. With the increase in stress, a small number of infrasonic wave events occur. In the stage from 70s to 185s, the relative energy of infrasonic waves shows the characteristic of near-linear increase. This stage corresponds to the elastic deformation in the deformation of the coal sample. According to the expansion-dilatancy theory[22], the relative energy of infrasonic waves shows this pattern mainly because, under the action of loading stress, the deformation of the coal sample is dominated by compression, which, coupled with the air, generate infrasonic wave events. With the increase of the loading intensity, the compression is increased and infrasonic wave events are more intense. Therefore, the relative energy of infrasonic waves shows a gradual upward trend. After loading to 185s, the relative energy of infrasonic waves shows a decreasing trend. This stage corresponds to the plastic and subsequent deformation of the coal sample, dominated by expansive deformation. According to the research on the sound wave features of the seismogenic body in the expansion-shrinkage process, the amplitude of sound pressure generated in the compression process is much larger than that generated during the expansion process. Therefore, when the dominant deformation of the coal sample changes from compression to expansion, the sound wave amplitude decreases gradually, and more faster with the aggravation of expansion. So the relative energy of infrasonic waves shows a feature of decreasing trend.

For coal sample 2#, before loading to 90s, the relative energy of infrasonic waves increases slowly. This stage corresponds to the compression in the deformation of the coal sample, which is dominated by the closing of pores and fissures. With the increase in stress, infrasonic wave events increase. In the stage from 90s to 225s, the relative energy of infrasonic waves shows the characteristic of near-linear increase. This stage corresponds to the elastic deformation in the deformation of the coal sample, dominated by compressive deformation. With the increase of the loaded stress, the compression is increased and infrasonic wave events are more intense. Therefore, the relative energy of infrasonic waves shows a linear increase. After loading to 225s, the relative energy of infrasonic waves shows a slow decreasing trend. This stage corresponds to the plastic and subsequent deformation of the coal sample, dominated by expansive deformation. With the loading continuing, the expansion inside the coal sample is increased while the infrasonic wave events are less intense. Therefore, the relative energy of infrasonic waves shows a feature of decreasing trend.

Based on the analysis of the variation features of the relative energy of infrasonic waves in the coal sample loading process, we find that, during the loading process, the relative energy of infrasonic waves change in stages, which include slow increase, near-linear increase towards the peak, and gradual decrease. These stages are consistent with the deformation stages of coal samples, so we can predict the deformation of coal samples according to the features in the relative energy of infrasonic waves. In particular, in the process from elastic deformation to plastic deformation, the relative energy of infrasonic waves changes from near-linear increase to gradual decrease, which is very obvious and easy to identify, so coal sample failures can be predicted according to this feature; in other words, when the relative energy of infrasonic waves changes from linear increase to slow decrease, the coal sample transits from elastic to plastic deformation, meaning the coal sample is about to fail.

4.4 Discussion

Through test and analysis on the change features of infrasonic waves in the coal sample loading process, we have established the relationship between the deformation of the coal sample and the response of infrasonic waves, and the precursor features of infrasonic waves before any failure of the coal sample.

In the loading process, the relative energy of infrasonic waves change in stages, which include slow increase, near-linear increase towards the peak, and gradual decrease. These stages are consistent with the deformation stages of coal samples, so we can predict the deformation of coal samples according to the features in the relative energy of infrasonic waves. In the past, researchers have done researches on the variation features of infrasonic waves in the loading process, but these researches mostly focused on the frequency and temporal frequency features and energy changes of infrasonic waves in the loading process[10,20,21], and few has been done on the response features of infrasonic waves in different deformation stages of coal samples, especially the relationship between the coal sample deformation stages and the relative energy of infrasonic waves.

By analyzing the change patterns of the relative energy of infrasonic waves, we have identified the precursor features of coal sample failures, i.e., when the relative energy of infrasonic waves changes from near-linear increase to gradual decrease, the coal sample transits from elastic deformation to plastic deformation, meaning the coal sample is about to fail. So far, researchers have studied the change features of infrasonic waves during the loading of coal samples, but few has been done on the obvious precursor features.

By analyzing the relationship between the change features of the relative energy of infrasonic waves in the coal sample loading process and the deformation of coal samples, we have identified the change features of the relative energy of infrasonic waves in the deformation and failure stages, and at the same time, we have conducted uncoupled acquisition and pre-processing of infrasonic wave signals and established a set of feasible infrasonic wave prediction methods for coal sample failures. Other researchers have conducted similar studies before, but these are mostly focused on feasibility studies. They have proved the generation of infrasonic waves[10], but have not identified the features of infrasonic waves during deformation and failure of coal samples. Therefore, we are the first to propose a feasible infrasonic wave prediction method for coal sample failures, and do not know if there is any other similar research result.

5. Conclusions

By analyzing the features of infrasonic waves in the loading of coal samples, we obtain the following conclusions:

(1) In the loading process, the relative energy of infrasonic waves change in stages, which include slow increase, near-linear increase towards the peak, and gradual decrease. These stages are consistent with the deformation stages of coal samples, so we can predict the deformation of coal samples according to the features in the relative energy of infrasonic waves;

(2) In the process from elastic deformation to plastic deformation, the relative energy of infrasonic waves changes from near-linear increase to gradual decrease, which is very obvious and easy to identify and thus can be used as a precursor feature for coal sample failures; in other words, coal sample failures can be predicted according to this feature;

(3) We conduct uncoupled acquisition and pre-processing of signals, establish a relationship between infrasonic wave signals and coal sample deformations and developed a set of feasible infrasonic wave prediction methods for coal sample failures, which make up for the drawbacks of the acoustic emission prediction method like non-coupled contact and fast attenuation.

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References

1. Ripepe, M., Poggi, P. and Braun, T. et al. (2013): “Infrasonic waves and volcanic tremor at Stromboli.” *Geophys Res Lett*, vol.23, no.2, pp.181-184, 2013.
2. Takashi, M. and Hiroyuki, S. (2014): “Infrasonic sounds excited by seismic waves of the 2011 Tohoku-oki earthquake as visualized in Ionograms.” *J Geophys Res-space*, vol. 119, no.5, pp. 4094-4108, 2014.
3. Wang, T., You, S. and Pei, F. et al. 2017): “Instability mechanism and control technology of coal pillar bumps under hard roof.” *J Min Safety Eng*, vol.34, no.1, pp. 54-59, 2017.
4. Johnson, J. B., Aster, R. C. and Ruiz, M. C. et al. (2009): “Interpretation and utility of infrasonic records from erupting volcanoes.” *J Agr Food Chem*, vol.55, no.5, pp. 1832-1838, 2009.
5. Chebotareva, I. Y., Volodin, I. A. and Dryagin, V. V. (2017): “Acoustic effects in the deformation of structually inhomogeneous media.” *Acoust Phys*, vol.63, no.1, pp. 86-94, 2017.
6. Tsuyoshi, I., Tadashi, K. and Yuji, K. (2010): “Source distribution of acoustic emissions during an in-situ direct shear test: Implications for an analog model of seismogenic faulting in an inhomogeneous rock mass.” *Eng Geol*, vol.110, no. 3/4, pp. 66-76, 2010.
7. Garces, M. A. (2000): “Infrasonic signals generated by volcanic eruptions.” *IEEE 2000 Int*, vol.3, no.7, pp. 24-28, 2000.
8. Majewska, Z. and Mortimer, Z. (2006): “Chaotic behavior of acoustic emission induced in hard coal by gas sorption desorption.” *Acta Geophys*, vol.54, no.1, pp.50-59, 2006.

9. Ostapchuk, A. A., Pavlov, D. V. and Markov, V. K. et al. (2016): "Study of acoustic emission signals during fracture shear deformation." *Acoust Phys*, vol.62, no.4, pp. 505-513, 2016.
10. Wei, J. P., Liang, S. J. and Wang, Y. G. et al. (2016): "Feasibility study on infrasonic wave monitoring dynamic disasters in coal and rock." *Prog Geophy*, vol.31, no.2, pp. 0814-0820, 2016.
11. Matoza, R. S., Le, P. A. and Vergoz, J. et al. (2010): "Infrasonic observations of the June 2009 Sarychev peak eruption, Kuril Islands: Implications for infrasonic monitoring of remote explosive volcanism." *J Volcanol Geoth Res*, vol.200, no.2, pp.35-48, 2010.
12. McKenna, M. H., Gibson, R. G. and Walker, B. E. et al. (2012): "Topographic effects on infrasound propagation." *J Acoust Soc Am*, vol.131, no.1, pp.35-46, 2012.
13. Guo, Q., Yang, Y. C. and Lü, J. et al. (2014): "Observation of Local Infrasound Coupled by Seismic Wave on Wide Spread Infrasound Network." *Earth Sci-J Chin University Geo*, vol.39, no.12, pp.1807-0817, 2014.
14. Johnson, J. B. (2003): "Generation and propagation of infrasonic airwaves from volcanic explosions." *J VolcanoL Geoth Res*, vol.121, no.1-2, pp.1-14, 2003.
15. Che, I. Y., Kim, G. and Pichon, A. L. (2013): "Infrasound associated with the deep M 7.3 northeastern China earthquake of June 28, 2002." *Earth Planets & Space*, vol.65, no.2, pp. 109-113, 2013.
16. Arnold, K., Johannes, H. and Emma, S. et al. (2014): "Infrasound produced by debris flow: propagation and frequency content evolution." *Nat Hazards*, vol.70, no.3, pp. 1713-1733, 2014.
17. Thüring, T., Schoch, M. and Herwijnen, A. V. et al. (2015): "Robust snow avalanche detection using supervised machine learning with infrasonic sensor arrays." *Cold Reg Sci Technol*, vol.111, no.111, pp. 60-66, 2015.
18 Valerie, L., Nicholas, Zimmer S. (2015): "Detection and location of rock falls using seismic and infrasound sensors." *Eng Geol*, vol.193, pp. 49-60, 2015.
19. Christoph, P., Carsten, S. and Florian, S. et al. (2013): "Airglow observations of orographic, volcanic and meteorological infrasound signatures." *J Atmos Sol-terr Phy*, vol.104, no.104, pp.55-66, 2013.
20. Zhu, X., Xu, Q. and Zhou, J. et al. (2013): "Experimental study of infrasonic signal generation during rock fracture under uniaxial compression." *Int J Rock Mech Min*, vol.60, no.2, pp.37-46, 2013.
21. Xu, H. and Zhou, T. Q. (2016): "Energy characteristics of infrasound abnormality during rock deformation and failure of rock." *Chin J Geotec Eng*, vol.38, no.6, pp. 1044-1050, 2016.
22. Qin, F., Zheng, F. and Li, J. Z. et al. (2007): "Mechanism Model of Infrasonic Wave Abnormality Before Strong Earthquakes." *J Beijing University Technol*, vol.33, no.1, pp.104-107, 2007.

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3. Liu, L. (2001): "Research on the Outburst prevention technology of multi-layer protection layer of coal seam group," *Mining Safety and Environmental Protection*, vol. 28, no. 5, pp. 1-4, 2001.
4. Cheng, Y. P., Zhou, D. Y. and Yu, Q. X. (2006): "Research on the drainage and emission law of protective seam," *Journal of Mining and Safety Engineering*, vol. 23, no. 1, pp. 12-18, 2006.
5. Bi, Y. W. (2011): "Study on the influence of protective seam mining on the permeability of coal seam," M.S. thesis, Dept. Liaoning, Liaoning Engineering Technology University, China, 2011.
6. Dai, G. L., Wang, Y. Q. and Zhang, C. R. (2007): "Forecast of the gas effused from the face in protective seam," *Journal of China Coal Society*, vol. 32, no. 4, pp. 382-385, 2007.
7. Wu, J. T., Shi, X. Q. and Qian, G. F. (2011): "Comprehensive gas management and utilization technology of the protective covering," *Coal Mine Safety*, vol. 42, no. 2, pp. 23-26, 2011.
8. Tu, D. H. (2008): "Study on protection scope and effect of protection layer mining," *Coal Technology*, vol. 27, no. 7, pp. 63-65, 2008.
9. Liu, M. J., Wang, M. and Li, B. (2010): "Study on Effect Evaluation of Protective Seam Mining," *Coal Science and Technology*, vol. 39, no. 1, pp. 61-64, 2010.
10. Tu, M., Miu, X. B. and Huang, N. B. (2006): "Study on deformation rule of protected seam after lower protective layer mining," *Journal of Mining and Safety Engineering*, vol. 23, no. 3, pp. 253-257, 2006.
11. Chen, Y. P., Yu, Q. X. and Yuan, L. (2003): "Mobile characteristic of the overlying removable rock mass and the gas extraction technology," *Journal of Liaoning University of Engineering and Technology: Natural Science Edition*, vol. 22, no. 4, pp. 483-486, 2003.
12. Xiong, Z. Q., Li, H. M. and Wang, W. (2009): "Study on the mining technology of remote protection layer in PingDingShan mining area," *Coal Science and Technology*, vol. 37, no. 8, pp. 53-56, 2009.
13. Shi, B. M., Yu, Q. X. and Zhou, S. N. (2004): "Numerical simulation of fracture deformation of long distance coal rock in protective layer," *Journal of China Mining University*, vol. 33, no. 3, pp. 259-263, 2004.
14. Qin, Z. H., Pan, J. F. and Ren, Y. (2010): "Mechanism of pressure relief for thin coal seam as protection seam." *Coal Mining Technology*, vol. 15, no. 2, pp. 85-88, 2010.
15. Shen, R. X., Wang, E. Y. and Liu, Z. T. (2011): "Rock burst prevention mechanism and technique of close-distance lower protective seam mining," *Journal of China Coal Society*, vol. 36, no. 1, pp. 63-67, 2011.
16. Cao, C. P. (2006): "Practices in coal mining under top protection strata with closed distance," *Coal Science and Technology*, vol. 34, no. 4, pp. 33-35, 2006.