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Predicting points of the infrared precursor for limestone failure under uniaxial compression

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1. Introduction

Rock is a type of complex geological material. Under external loads, rock mechanical behaviour features great complexity, fuzziness and nonlinearity. Thus, the study of rock fracturing and failure under stress has become a problem of focus and is of widespread interest in geosciences and geo-engineering, including tunnel collapse, slope stability and coal-rock disasters in mines. In recent years, ore has been extracted at deeper depths in the mining field, and rock disasters have become more likely to occur than ever before, which not only endangers mining workers but also suspends production. However, in rock engineering, anomalous phenomena appear before rock failure and contain abundant useful information. Anomalies prior to rock failure are important and provide useful precursory information to predict rock failure and instability. Thus, it is of great significance to capture the precursor and distinguish relevant precursor points, which is helpful in in situ monitoring and disaster forecasting.

An object whose temperature is above absolute zero K will emit electromagnetic radiation (EMR), including mid-infrared waves (1.5–6 μm) and far-infrared waves (6–15 μm), which has the thermal effect.[1] Under external loads, rocks and rock-like materials are accompanied by certain physical and chemical phenomena—e.g., acoustic emission (AE), infrared radiation (IRR) and light radiation. The evolution of the deformation and failure process inside the materials could be reflected by monitoring the radiation signal variation features, and it could provide important and useful information for predicting rock failure. Infrared thermography (IRT), a non-destructive, noncontact and real-time technique, could be used to monitor the damage evolution and the material degradation. During past decades, IRT has been widely applied to damage characterization, defect detection and failure prediction in materials or structures such as metal, alloys and composites.[2–7] The IRT technique has also been extensively used in the field of rock mechanics—e.g., the infrared thermovision of rock damage processes,[8] the precursor study on bump-prone coal failure,[9] the infrared radiation characterization of rocks under loading,[10–13] the description of projectile impact on rock,[14,15] and the excavation damage characterization of physical models of rocks.[16]

Abnormal increases in crust surface radiation temperature were observed in thermograms of climate satellites days or weeks before many strong earthquakes in most recent years.[17] Enhanced thermal infrared (TIR) emission recognized in satellite images of the earth's surface prior to major earthquakes is known as a "thermal anomaly".[18] Anomalous increases in land surface temperature (LST) due to TIR anomalies before impending earthquakes have been successfully verified in the last decade.[19–21] In laboratory testing, an IRR anomaly was also viewed before rock failure in simulated experiments for earthquake precursor studies.[22,23] The new inter-discipline of remote sensing rock mechanics (RSRM) was put forward, and it could serve in the forecasting of the time–space location of potential rock failure events by IRR monitoring.[1] Based on a series of experiments of IRR features for multiple rocks under different loading conditions, it was revealed that the detected temperature would reflect the IRR energy variation and that the abnormal IRR precursors could provide forewarning information for rock failure prediction.[24–26] Wu and Wang[27] concluded that $0.79\sigma_c$ (σ_c is the compressive strength) could be suggested as the precursor point for stability evaluation of coal and rock and for ground pressure prediction. Wu et al.[28] found that thermogram abnormality and temperature curve abnormality were detected as precursors of rock fracture. Three precursor messages—short dropping, fast rising and dropping-to-rising—were observed by

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studying the temporal evolution features of average infrared radiation temperature curves.[29]

Based on the quantities of IRR investigations on materials subjected to loads, IRR anomalies, including the thermogram abnormality and temperature curve abnormality, were detected and could be considered as the important precursor for rock failure and instability. However, owing to the complexity of rock failure, this method is limited in terms of accuracy and reliability when using only a single analytic method—e.g., temperature curve analysis or thermogram characterization—to predict rock failure. In contrast, it is more accurate and reliable to synthetically consider the abnormalities of both the thermogram and temperature curve. In this study, during the entire deformation and fracturing process, the IRR features were analysed on the surface of loaded limestone samples under uniaxial compression. The original thermogram data were processed by the thermogram subtraction method, and the differential thermograms were obtained. The mean temperature curve variations with time and the spatio-temporal evolution of differential thermograms were analysed comparatively to investigate the IRR precursor point of rock failure and instability.

2. Experiment and methods

2.1. Experimental instruments

An experimental system comprising the loading machine and the thermographic camera was utilized in the experiment. The loading system is a TAW-2000 computer control electro-hydraulic server with loading precision 0.5%. An uncooled infrared FPA thermographic camera InfRec R300, manufactured by the Nippon Electric Company in Japan with temperature precision of 0.05 °C, spatial resolution of 1.2 mrad and graphical resolution of 320 × 240 pixels, was applied to detect the IRR changes in the rock samples. The detection temperature range of InfRec R300 is from 10 °C to 40 °C, and the highest graphic recording rate is 60 frames per second. The thermographic camera operates in the spectral range from 8 to 14 μm, and the surface temperature can be measured in the 8–14 μm infrared atmospheric windows. At the scarcely absorbed continuum of wavelengths (8–14 μm), the emitted radiation mostly passes unabsorbed through the atmosphere with little attenuation, which offers a potential advantage in terms of the accuracy of temperature determination. The thermogram data are stored in the InfRec R300 in the time sequence and can be analysed by the affiliated NS 9500 software.

2.2. Experimental methods

In this experiment, ten limestone specimens were collected from the roof of a coal seam at a depth of 1100 m in Xiezhuang Mine, Shandong Province, China. Before the experiment, these samples were processed as standard cylindrical rock samples of 50 mm in diameter and 100 mm in length. The specimens' ends were polished, and the tolerance of parallelism was less than 0.05 mm. During the experiment, the limestone specimens were loaded under uniaxial compression with axial equivalent displacement control, and the loading speed was controlled at 0.5 mm/min. Regarding the thermographic camera, the graphic recording rate was set to 4 frames per second. The InfRec R300 directly faced the rock sample surface approximately 1 m from the samples. The IRR on the rock surface was debugged to ensure stability before the rock samples were loaded. The ambient temperature and humidity in the laboratory were tested before the experiment. The ambient temperature was 22.10 °C, and the humidity was 29%. The emissivity of the tested limestone sample was 0.92. In the experiment, the TAW-2000 and InfRec R300 were operated simultaneously during the entire deformation and fracture processes on the limestone samples.

3. Theoretical bases of IRR detection for rocks

Temperature is a comparative objective measure of hot and cold. It reflects the thermal state of the object and can be measured in a contact or noncontact way. The noncontact mode is based on the measurement of the IRR emitted from the object surface. Heat radiation, or thermal radiation, is the emission of electromagnetic waves from all matter with a temperature greater than absolute zero. It is among the three fundamental modes of heat transfer and represents a conversion of thermal energy into electromagnetic energy. Examples of thermal radiation include visible light emission and infrared light radiation. According to the electromagnetic spectrum, IRR is invisible infrared light emission with wavelength higher than that of visible light and lower than that of microwaves, ranging from approximately 760 nm to 1000 μm. In addition, the physical mechanism of infrared radiation may be the energy jump of molecule oscillation or rotation. In general, objects emit IRR across a spectrum of wavelengths. However, infrared wave transmission could be easily absorbed and scattered by the atmosphere with much attenuation. In the infrared atmospheric windows of 3–5 μm and 8–14 μm, the emitted radiation offers a potential advantage in terms of the accuracy of temperature determination. The thermographic camera commonly operates in the infrared atmospheric window wavelengths. Thus, based on the theory and application of IRR, IRT is a well-established technique in non-destructive testing and has been extensively used in temperature measurement, damage characterization, and defect detection of materials.

In thermal radiation theory, Planck's law is the basic law for black body radiation. Planck's law theoretically demonstrates the relationship among spectral radiance, the wavelength and the thermodynamic temperature of the black body. Planck's law is given as[30]

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5}\cdot\frac{1}{e^{ch/\lambda kT} - 1} \tag{1}$$

where B_λ is the spectral radiance, W m^{-2} μm^{-1}; h is Planck's constant, J s; c is the speed of light, m s^{-1}; λ is the wavelength, μm; k is the Stefan–Boltzmann constant, J m^{-2} K^{-4}; and T is the absolute temperature of the object, K.

Planck's law gives the spectral blackbody emissive power distribution in thermal equilibrium at different temperatures. The spectral radiance of a body indicates the amount of energy it gives off as radiation of different wavelengths. It is also revealed that the higher the temperature of a body, the more radiation it emits at every wavelength. In addition, the Planck radiation has a maximum intensity at a specific wavelength that depends on the temperature. Therefore, the radiant properties of a black body are dependent only on the absolute temperature and have nothing to do with the material composition.

In this study, the thermographic camera was applied in the passive mode without the use of any extra heat resources. The IRT visualized the temperature changes over the viewed rock surface. When the rock samples were loaded, the thermographic camera was employed to observe and capture the IRR variation during the entire loading process. In the IRR detection experiment, the temperature data and the thermograms of the rock surface would be obtained. The IRR emitted from the rock surface was detected by the focal plane array (FPA) detector in the thermographic camera. By calibration, the relation between surface temperature and

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