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Thermal image and spectral characterization of roadway failure process in geologically 45° inclined rocks

Weili Gong, Yanyan Peng, Manchao He *, Jiong Wang

State Key Laboratory for Geomechanics & Deep Underground Engineering, Beijing 100083, China
School of Mechanics and Civil Engineering, China University of Mining & Technology, Beijing 100083, China

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ABSTRACT

Large-scale geomechanical model test was conducted in order to investigate stability of an un-supported tunnel with rectangular cross section embedded in 45° inclined alternating strata of sandstone, mudstone and coal seam. The loading path consists of two groups: cases A–G with overburden depths from 296 to 948 m and small loading rate, and cases H–M with overburden depths from 1126 to 2047 m and fast loading rate. Infrared thermography, incorporated with image processing and Fourier transform, was employed to characterize the rock responses. Averaged temperature field, $\langle IRT \rangle$, represents energy release rate, oscillating at stick–slip pattern with different periods and amplitudes. Overburden depth and loading speed have a significant impact on $\langle IRT \rangle$ curve, i.e. small overburden depth and loading speed corresponds to long period and small amplitude; whereas, great overburden depth and fast loading speed to short period and high amplitude. The processed thermal image best represents rock behavior by two major IRT distribution modes. For loading cases A–G, the coal strata were over stressed indicated by high IRT while the mudstone strata were less stressed represented by low IRT, corresponding to the static interlayer friction. For loading cases H–M, the mudstone strata were over stressed indicated by high IRT while the coal strata were less stressed indicated by low IRT, corresponding to the dynamic friction. Fourier spectra and spatial frequency were employed to characterize the infrared sequence. Ultra-high spatial frequency component is a precursor for predicting the imminent dynamic event. Low spatial frequency component may be served as an indicator of the tunnel-wide sphere of influence that the stress redistribution extends.

1. Introduction

Sedimentary rocks cover the majority of earth's surface and are frequently encountered in underground mining. In the sedimentary rocks, two main sources of discontinuities are beddings and joints. The beddings can be assumed continuous over areas greater than that of any designed excavation. The joints however, are typically constrained between beddings. Both beddings and joints are surfaces of relatively low shear strength and negligible tensile strength. Under the condition of stratified rock masses stretching across the roadway section, the engineering geological behavior during roadway development and operation is mainly controlled by the characteristics of the stratification planes (Fortsakis et al., 2012). Existence of these discontinuities may exert a marked impact on the reduction of rock strength and stiffness of the rocks (Sagong and Bobet, 2002). Stability analysis of the excavations in sedimentary rocks should account for geometrical and mechanical properties of the discontinuities (Tesarsky, 2012).

Extensive researches have been conducted on tunneling, roadway excavation and reinforcement, block caving and stability of the underground caverns in sedimentary rocks including, for example, in-situ tests (Read, 2004; Li et al., 2008); analytical studies (Lydzba et al., 2003); numerical modeling using finite difference method (FEM) (Tsesarsky, 2012), finite element method (FEM) (Fortsakis et al., 2012; Golshani et al., 2007), discrete element method (DEM) (Heuze and Morris, 2007), discontinuous deformation analysis (DDA) (Tsesarsky and Hatzor, 2006; Hatzor and Benary, 1998; Mazor et al., 2009; Zuo et al., 2009), and physical model tests (Lee and Schubert, 2008; Sharma et al., 2001; Kamata and Masimo, 2003; Zhu et al., 2011; Fekete et al., 2010; Liu et al., 2003; Castro et al., 2007; Shin et al., 2008; Li et al., 2013). Well designed experiments and judicious choice of model materials and their response and matching this with stress levels may yield important views into failure modes and mechanisms that are not available from numerical models (Zhu et al., 2011).

* Corresponding author at: School of Mechanics and Civil Engineering, China University of Mining & Technology, Beijing 100083, China.
E-mail address: manchaohecumtb@163.com (M.C. He).

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In order to capture the geotechnical information about detailed rock conditions and responses, the use of remote sensing equipment is often required during in-situ or laboratory tests. Laser scanning and photogrammetry are two imaging techniques widely used in a tunnel environment. Digital imaging system for determining displacement and strain has been applied in recent decades to a number of geotechnical engineering problems (Gaich and Potsch, 2008; Birch, 2008; Lee and Bassett, 2006), and recently used successfully to measure convergence around cavern in large-scale three-dimensional geomechanical model tests (Zhu et al., 2010, 2011). The photogrammetry, as reviewed by Fekete et al. (2010), requires supplementary lighting while three-dimensional laser scanning (Lidar) acts as its own source of "illumination" (Kim et al., 2006; Birch, 2008). The Lidar was applied but not limited to the evaluation of rock reinforcement (Gosliga et al., 2006), landslide monitoring (Strouth and Eberhardt, 2005), and stratigraphy modeling (Buckley et al., 2008). Fekete et al. (2010) used improved Lidar in active tunneling environment under dusty, damp, and dark conditions and collected very accurate, high resolution 3-dimensional images of its surroundings.

The advantages of employing non-contact optical vision techniques lie in their ability to represent the structural change by realistic and practical surface models or geometrical features. Usability of the detected geometrical features such as cracks and discontinuities, however, depends on the image resolution and does not has a definite relation to stress redistribution in the surrounding rocks. Infrared (IR) thermography is another non-contact and remote sensing technique which produces thermal image in real time by detecting electromagnetic waves within IR wave band (Luong, 1995). Thermal image represents rock response based on the thermal–mechanical coupling effect (Luong, 2007) and does not require supplementary lighting as well. When processed with proper algorithms, thermal image will not only be able to detect geometrical features such as crack propagation, but also the static and dynamic friction (He et al., 2010a) which could hardly be observed by the conventional optical visualization techniques. Thermography matrix data set is in fact the IR radiation temperature field on the surface in view induced by energy release of the cracking rocks. The fact that frequency-spectra of the thermal image can represent the seismic wave propagation is the intrinsic advantage of the thermography that the optical imaging technique does not possesses.

IR thermography has been widely used in detecting damage in the deformed materials such as composite (Connolly and Copley, 1990), carbon fiber reinforced polymers (Steinberger et al., 2006), metals (Luong, 1995; Pastor et al., 2008), and rocks (Brady and Rowell, 1986; Luong, 1990, 2007; Grinzato et al., 2004; Wu et al., 2006; Shi et al., 2007). In recent decades, IR thermography has been employed to detect the excavation damaged zone (EDZ) in the large-scale geomechanical model tests for simulation of tunnel excavations at China University of Mining and Technology Beijing (CUMTB). Compared to detection of small-scale laboratory specimens with infrared thermography, major difficulty encountered in detecting the large-scale geomechanical models is the small signal to noise ratio (SNR) of the raw image due to lower spatial resolution defined by imaging area per pixel. Hence enhanced imaging processing algorithms were developed to analyze the thermal images (Gong et al., 2013a). To date, the reported experimental investigations at CUMTB involved the excavation in 0°, 45°, 60° and 90° inclined stratified rocks (He et al., 2010a,b; He, 2011; Gong et al., 2013b). However, detecting the large-scale geomechanical model tests on tunnel stability embedded in steeply inclined rocks using infrared thermography was rarely addressed in the published literatures.

Stability of the underground opening increases as the joint set dip is flattened, and decreases when it is steepened (Heuze and Morris, 2007). The lowest strength of the rock masses correspond to the dip angles ranging from 40° to 50°, evidenced by the systematic studies using large-scale geomechanical model tests and numerical simulations (Zhu and Zhao, 2004). A large number of coal mine in China have thick and steeply inclined coal seams, and mining of them tends to result in geological disasters such as coal bumps, coal and gas outbursts, and ground subsidence and floor heave (Dai et al., 2013; Ju et al., 2006). Failure mechanisms of the steeply inclined rocks, however, have not yet been fully understood due to the problem complexity. One of the major difficulties in the large-scale physical model tests on the steeply inclined strata lies in the monitoring the frictional slip behavior. The objective of this research is to investigate frictional failure behavior of the steeply inclined strata with an un-supported tunnel using large-scale geomechanical model test and infrared thermography. The dip of 45° was selected based on the above reviewed findings by Zhu and Zhao (2004). In addition to thermal image analysis with the state-of-the art algorithm, the loading rate and Fourier spectra were utilized to analyze high and low *spatial frequency* precursors on rock failure.

2. Experimental

The field case simulated in this research is a main haulage roadway under operation in QISHAN underground coal mine, located in Xuzhou coal mining district, eastern China. The mining depth of this mine at present is ranging from 300 to 1000 m and will proceed to greater depth of more than 1000 m in the future. For construction of the large-scale physical model consisting of 45° inclined strata, both the field investigation and laboratory specimen tests were carried out. Detailed description of the prototype can be found in our previous publications (He, 2011; Gong et al., 2013b).

2.1. Testing machine

Fig. 1 shows the 'YDM-C Geological Disaster Simulation Testing Machine" for performing the quasi-two-dimensional large-scale geomechanical model test. The tester consists of a gate-shaped steel frame, loading platens, hydraulic loading-control device,

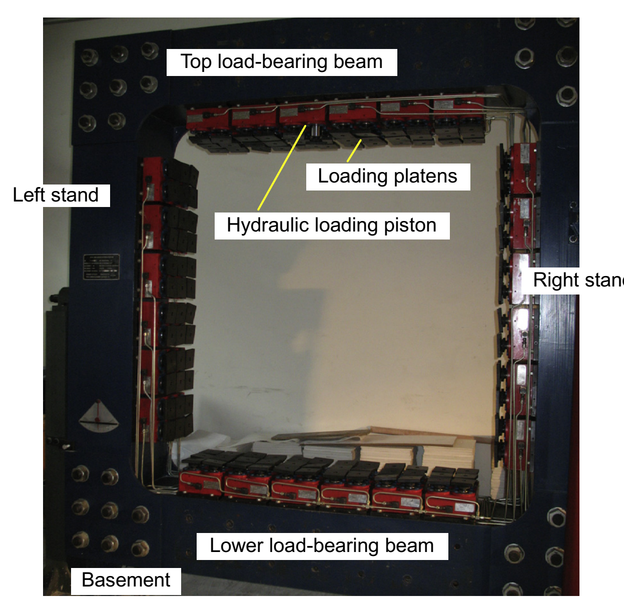

Fig. 1. Photograph of the YDM-C geological disaster simulation testing machine.