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Physical modeling of floor heave for the deep-buried roadway excavated in ten degree inclined strata using infrared thermal imaging technology

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ABSTRACT

The paper presents an experimental study on the floor heave of roadway excavated in deep ten degree inclined strata. During the processes of roadway floor heave, infrared thermography and video camera were employed for capturing the thermal response and displacement of roadway's section, meanwhile, strain gauges installed with a circular layout in surrounding rocks was used for measuring roadway sectional deformation. Floor heave and failure was investigated by the combined analyses of the acquired infrared images, video photographs and straining field variations. A numerical model was also implemented based on the physical model for verifying the tunnel displacements obtained by image analysis of the photographs. The results showed that the horizontal stress had a great effect on the floor heave failure and the rock mass failure was accompanied with abnormal temperature change.

1. Introduction

As the depleting of shallow buried resources, deep coal resources are coming into notice in more and more coal mines in China. With increasing of the mining depth, more than half of the deep buried roadways and chambers are threatened by large deformation (Kang et al., 2014). Floor heave is a kind of large-deformation failure, which also occurs in the deep buried roadway, causes a lot of money lose, and greatly affects the safety production (Sun et al., 2009, 2014). How to control the floor heave has become an important engineering problem. Therefore, study on the roadway floor heaving will be helpful to understand the mechanism of floor heave and even to resolve the problem.

In recent years, many scholars have studied the roadway failure and stability using varied methods including numerical simulation, laboratory experiments, and in-situ tests. Jiang's group studied on the mechanism of the floor heave by means of the theoretical analysis and the similarity simulation test (Jiang et al., 1994, 2004). From 2001, more and more researchers studied the mechanism and the control method of the floor heave using numerical simulation (Jing et al., 2001; Zhu et al., 2011a; Sun and Wang, 2011; Li and Liu, 2013; Lin et al., 2013; Zhao et al., 2015; Xu et al., 2016). Jeon et al. (2004) studied the excavation related problems by small–scale model tests. Lee and Schubert (2008) conducted small scale model tests to research the failure mechanism of tunnel faces. Zhu et al. (2011b) carried a Quasi-three-dimensional physical model test to study the failure mechanism of the caverns under high in-situ stresses. Tang and Tang (2012) studied the tunnel floor heave in swelling ground under humid conditions by numerical simulation. Zhong et al. (2012) analyzed the occurrence mechanism of floor heave for soft-rock tunnels by means of field investigations and geologic surveys. Many model tests were conducted to study the IRT (infrared temperature) feature of the surrounding when the roadways were excavated (He et al., 2009, 2010a,b; 2011; Gong et al., 2013a,b, 2015a,b). Chang et al. (2013) studied the control effect of the floor heave in the soft rock roadway with hydraulic expansion bolts support. Huang et al. (2013) studied the effect of weak interlayer on the failure pattern of rock mass around tunnel by a model test and numerical simulation. Lin et al. (2015a) conducted a geomechanical model test to investigate the failure behaviour and instability of the "large, deep, long and in-group" tunnels constructed in the Jinping II hydropower station. Lin et al. (2015b) analyzed the cracking, stability and reinforcement of the slope by a geomechanical model test. Li et al. (2015) used model tests to study the surrounding rock deformation and failure mechanisms of deep roadways with thick top coal. Yang et al. (2015) studied the mechanical behavior of a jointed rock mass adjacent to an underground excavation by numerical simulation and physical model test. Liu et al. (2015) used the physical model test to assess the stability of the Three-Gorges dam foundation, China. Chen et al. (2016) assessed the stability of brick-lined tunnels by Physical model tests and numerical simulation. Because field experiments and in-situ tests are limited both in time and

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costs (He, 2011), the physical model test and numerical simulation are the two more useful methods to conduct some research on the geotechnical engineering structures (Lin et al., 2015). Model tests play an important role in studying the stability and failure in the geotechnical engineering structure.

When the roadways were excavated, floor heave, as a kind of typical failure form of the roadway, occurred frequently. Meanwhile the inclination angle of the stratum produce influences on the stability and failure mechanism of the roadway. However, few physical model tests are used to study the floor heave failure and few scholars take the stratum inclination angle into the consideration. The infrared (IR) thermography, as a non-destructive, remote sensing technique, has been widely used in detection of the onset of unstable crack propagation and/or flaw coalescence for concrete and rock (Toubal et al., 2006). The physical model tests incorporated with IR thermometer have been carried out to research the roadway excavation in 0°, 45°, 60° and 90° inclined strata in our group, however the roadway has not been researched in 10° slightly inclined strata. In fact, there are some roadways in slowly inclined strata which the inclination angle is close to 10°. In our previous work, we mainly study the IRT feature of the surrounding rock when the roadway was excavated, and there are few study about the strain change feature and failure mechanism of the surrounding rock.

In the present paper, in order to study the floor heave of the roadway in deep slightly inclined strata, a reduced-scale physical model test equipped with state-of-the art Infrared thermometer and contact measuring methods was conducted to study the floor heave. The effect of the side pressure coefficient on the floor heave failure, failure pattern of the floor strata, and the stress variation of the surrounding rock under the different horizontal stress were investigated by using the infrared sequence, the strain and image datum. The features of temperature change were studied when the strata failure occurred. A numerical model was also implemented based on the physical model for verifying the tunnel's displacements. Finally the key position of the roadway floor heave failure was found. A deeper understanding of the mechanism of floor heave was achieved.

2. Physical model test

2.1. The simulation prototype

The depth of the transportation roadway studied in this paper is nearly 1000 m below the ground surface, which is located in Xuzhou coal mining district, in Jiang Su province, eastern of China. The main exposure stratum lithology is sandy mudstone, mudstone, and sandstone. The inclination angle of the strata is approximate 10°. According to the in-situ survey and laboratory specimen tests, the physical and mechanical parameters of the real rocks are listed in Table 1. The deformation features of this roadway are mainly shown as the following aspects. (1) The both sides of the roadway had large and asymmetrical deformations. (2) The serious failure of the roadway floor heave had seriously affected on the normal use of the roadway (Fig. 1). (3) The roof sustained asymmetrical force and the phenomenon of roof caving happened (Fig. 2). The roadway had appeared the typical floor heave failure in deep slowly inclined strata, although it was used as the simulation prototype to research roadway floor heave failure in the slightly inclined strata.

Table 1
Main physical and mechanical parameters of real rocks.

Rock types	Unit weight (kN/m^3)	Unconfined compressive strength (MPa)	Young's modulus/GPa
Sandstone	27	64	25.77
Mudstone	26	44	21.01
Coal-seam	14	26	5.01

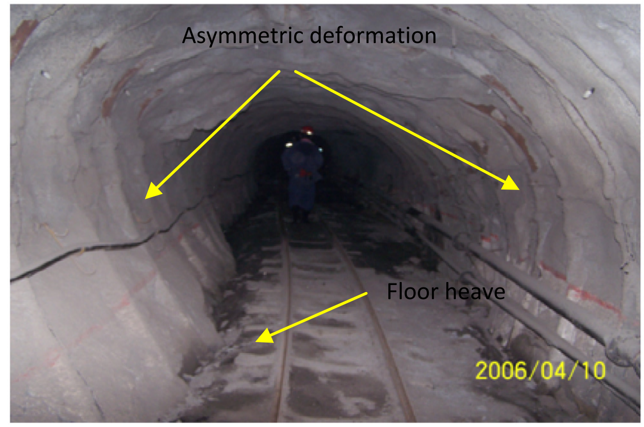

Fig. 1. Asymmetric deformation of the roadway and the floor heave.

Fig. 2. Roof caving.

2.2. Building physical model

Physical model experiments were used to simulate the practical geotechnical engineerings, the physical model is not a copy of the complexity natural phenomenon, but an abstraction and simplification of the practical geotechnical engineering. There are some physical similarity constants in the physical model experiment. When the stress and deformation of the surrounding rock are researched, the main physical similarity constants are as the following:

$$C_\sigma = \frac{\sigma_p}{\sigma_m}\ C_E = \frac{E_p}{E_m}\ C_\varepsilon = \frac{\varepsilon_p}{\varepsilon_m}\ C_\gamma = \frac{\gamma_p}{\gamma_m} \tag{1}$$

where C_σ is the stress similarity constant, C_E is the elastic modulus similarity constant, C_ε is the strain similarity constant, C_γ is the body force similarity constant.

Meanwhile the model and prototype should meet the differential equations of equilibrium, so the similarity index should meet the following requirement:

$$\frac{C_\sigma}{C_l C_\gamma} = 1 \tag{2}$$

where C_l is the geometric dimension similarity constant.