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Influence of structure and water pressure on the hydraulic conductivity of the rock mass around underground excavations

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ABSTRACT

In this study, in situ water injection tests and numerical modeling in conjunction with core logs and television image measurements were applied for an investigation of the hydraulic properties of the rock mass around underground excavations. The aim of our work was to investigate the influence of rock structure and water pressure on the hydraulic conductivity of the rock mass around underground excavations. Thus, water injection tests were conducted in four boreholes that were drilled in the rock mass in underground tunnels in China. Seepage connection initiation and steady state seepage were proposed to identify the seepage evolution course within the rock mass by combining the results of pressure and hydraulic conductivity. Generally, hydraulic conductivity is strongly related to rock structure and water pressure. The results also revealed that a rearrangement of rock structure would occur in the damage zone, resulting in an increase in hydraulic conductivity of nearly one to several orders of magnitude. The results from the modified numerical model showed that the pore water distribution and the groundwater inflow rate are affected by both the hydraulic conductivity and the thickness of the damage zone and they are influenced more by the thickness of this zone.

1. Introduction

Precise hydrogeological parameters are important for many underground applications ranging from nuclear waste isolation to coal and crude oil production and other infrastructures (Hamm et al., 2007; Ameli et al., 2014). Particularly, there has been increasing consideration of the hydraulic conductivity of rock masses (Bárbara et al., 2011). The hydraulic conductivity of undisturbed rock is influenced in the near field by the rock characteristics, such as the rock structure, the geometry of fractures, the initial stress field (Mas Ivars, 2006), and the water pressure within the fractures of the rock mass (hydro-mechanical coupling) (Fernandez and Moon, 2010a). Moreover, the formation of a damage zone is a phenomenon that occurs in most host rocks as a consequence of underground excavation (Fernandez and Moon, 2010a). One concern regarding underground excavation is that the initial rock characteristics could change due to the associated damage in the rock mass close to these excavations and thus influence the hydraulic conductivity (Blümling et al., 2007).

Extensive studies have addressed the problem of understanding the influence of structure and water pressure on hydraulic conductivity of the rock mass (Souley et al., 2001), which include in situ tests (e.g., Foyo et al., 2005; Sánchez et al., 2006; Zhu et al., 2013; Huang et al., 2014a, 2014b) and laboratory tests as well as numerical simulation methods (e.g., Souley et al., 2001; Oda et al., 2002; Chaki et al., 2008; Fernandez and Moon, 2010a, 2010b; Massart and Selvadurai, 2014; Chen et al., 2014). In situ tests are considered to be more useful than laboratory tests and numerical simulation methods because in situ test represents in situ conditions with a larger scale (Hamm et al., 2007).

The main objective of this study was to investigate the effect of structure and water pressure on the hydraulic conductivity of the rock mass by employing in situ water injection tests in the rock mass surrounding the underground excavations. In addition, this paper presents the pore water distribution and inflow rate variation considering the damage zone, which provides a basis for proposing an additional explanation for the influence of the damage zone on the hydraulic characteristics around underground excavations using numerical modeling.

2. In situ test measurements

2.1. Study area and test sections

The study area is located at the Yangcun coal mine in Shandong Province, Eastern China (Fig. 1a), where 18 seams of Permo-Carboniferous coal are named the No. 1 through No. 18 coal seams from top to bottom (Huang et al., 2014a). Yangcun mine was formally put on production on June 20, 1989, and its production capacity is 1.15 million tons. Yangcun mine has been mining the No. 16 and No. 17 coal seams since 1989. The rock masses under the coal consist

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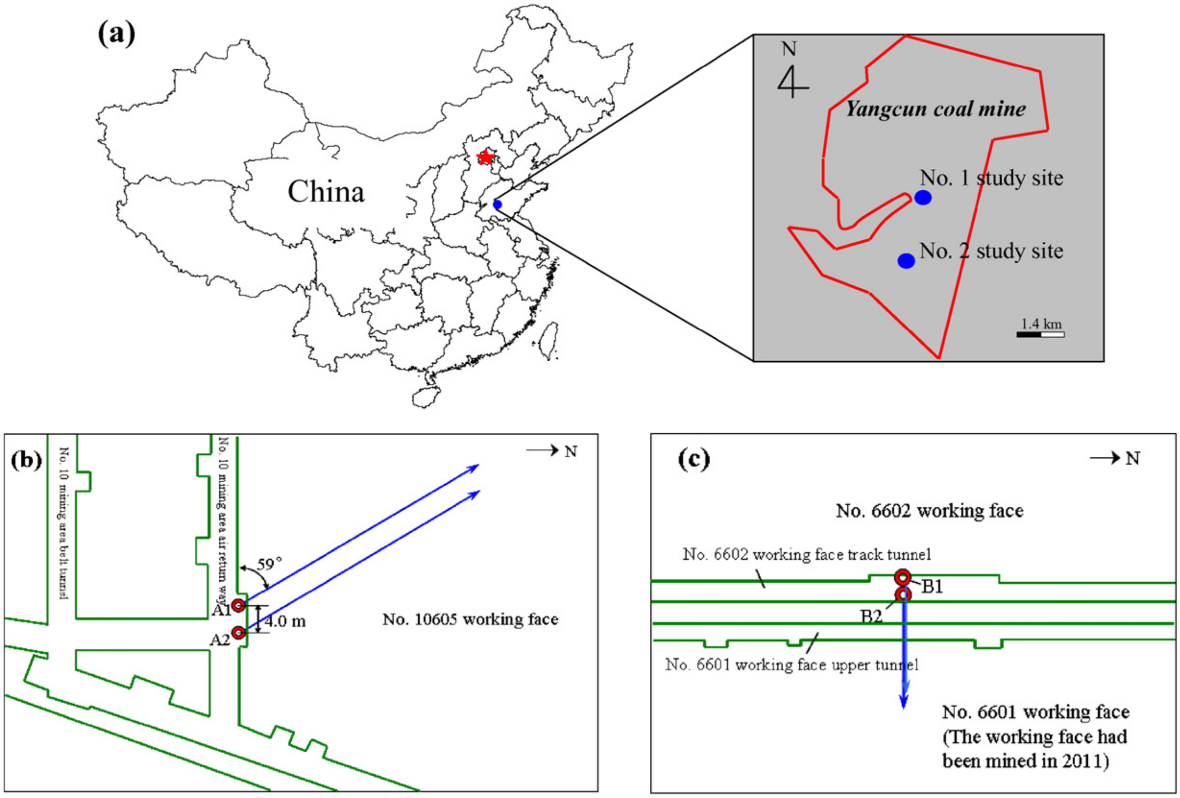

Fig. 1. Location plane graph of the study area and boreholes: (a) the map view; (b) location of the No. 1 study site; (c) location of the No. 2 study site.

of mudstone, sandstone, and limestone. From a hydrogeological point of view, the Ordovician limestone underlying the coal forms a confined karst aquifer containing an abundant supply of water and having very high water pressure (Zhang, 2005). However, the distance between the mined coal and Ordovician limestone is very short, ranging from 40 to 80 m, where the rock mass exhibits important processes of fracturing that have favored the development of a notable network of flow conduits (Bárbara et al., 2011). Thus, water from the Ordovician aquifer may flow into the working face through the flow conduits within the rock mass.

Our study is centered in the area between the coal and limestone aquifer, where the rock mass is considered to be the key waterproof material. The typical width and height of tunnels in underground coal mines in China are 3.5–5 m and 2.5–3.5 m, respectively (Kang et al., 2010). Thus, a tunnel is suitable for hydraulic conductivity measurements. The test sections consist of two types of rock masses: the initial intact rock and a damage zone. The in situ tests aim to investigate the difference in hydraulic characteristics between the initial intact rock mass and the damage zone. Fig. 2 shows the geotechnical boring logs of the test boreholes. Four boreholes (A1, A2, B1, and B2) were drilled (Fig. 1b, c). As shown in Fig. 2 and Table 1, A1 and A2 were 4 m apart, and both boreholes were drilled to a length of 48 m with a plunge of 30°; B1 and B2 were 3.5 m apart, both boreholes were drilled to a length of 30 m with a plunge of 26°. These two types of boreholes consisted of a total of six test sections. The No. 1 study site consisted of the first to third test sections, and the No. 2 study site consisted of the fourth to sixth test sections. The first test section was mudstone; the second, fourth, and sixth test sections were sandstone; the third test section was mudstone and limestone; and the fifth section was mudstone, limestone, and coal. The three sections of the No. 2 study site under the floor of the No. 6601 working face was a damage zone that had been induced by mining activities. The first section was also a damage zone that had been induced by tunnel drilling. Table 2 shows the physical and mechanical properties of several test sections. According to the drilling data of test boreholes and television images of B1 and B2, the structures of the first test section and the fourth to sixth sections were cataclastic structures, while the structures in the second and third test sections were thinly stratified structures. Two confined aquifers underlie the coal seams: the No. 14 limestone aquifer and the Ordovician limestone aquifer. The boreholes were not drilled to these aquifers. Moreover, grouting was used to seal off the other aquifers from the test sections.

2.2. Test method

A water injection test or Lugeon test (Lugeon, 1933) is used to investigate the hydraulic properties of a rock mass. Water injection tests (Jiang et al., 2007; Huang et al., 2014a, 2014b) were conducted in this study, as shown in Fig. 3. Two boreholes are drilled as part of a water injection test, with one borehole used to inject water and the other to monitor data. When the boreholes are drilled, casing pipes are installed in the boreholes from the orifice to the top of the test section to seal the test section off from the surrounding rock mass. The open section below the casing pipe is the test section (Fig. 3). The sensors are installed in the observation borehole and then connected to a data recording instrument by cables. The injection borehole is connected to a pump, a flow meter, and a pressure gauge. Water is then injected into the test section in a sequence of pressure levels according to pressure test methodology (Sánchez et al., 2006; Bárbara et al., 2011). Each pressure level is held for a specified number of minutes. The water pressure and flow rate are continuously measured during the injection.

2.3. Test procedure

After the study area and test sections have been selected, the water injection test is conducted in the following stages.

(1) The injection borehole and observation borehole are drilled to the designed depth. Generally, boreholes are drilled to the upper apex of the test section.