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Characterizing the hydraulic conductivity of rock formations between deep coal and aquifers using injection tests

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ABSTRACT

The hydraulic behavior of the rock formations under coal floor is an important factor to evaluate the risk of floor water inrush, which is difficultly obtained exactly by laboratory hydraulic tests. For the purpose of obtaining the hydraulic conductivity of the rock formations between deep coal and aquifers and further evaluating the risk of floor water inrush, water injection tests are carried out at Baodian coal mine. Through drilling four boreholes, three water injection tests of three rock formations are carried out and the hydraulic conductivity of the rock formations is calculated. Experimental results analysis shows that the three test rock formations are low-permeability. The hydraulic conductivity propagation with injection pressure can be divided into two phases that include stable change phase and increase phase due to hydraulic fracturing. In addition, the crack connections and propagations model can be used to analyze the change process of hydraulic conductivity of rock formations under water pressure. It is a useful approach for obtaining the hydraulic conductivity of deep rock formation, evaluating the risk of floor water inrush, preventing water inrush and raising the coal mining efficiency in colliery.

1. Introduction

Coal mine water inrush accidents have resulted in hundreds of fatalities in many countries including Great Britain, India, and United States of America since the 19th century [1–4]. And the past decade has seen the rapid development of the coal industry in China; meanwhile, water inrush accidents have been occurring and deeply threatening coal mine workers' safety and coal production in China since the 1950s [5]. Furthermore, the risk of coal mine water inrush is becoming serious with the increase of mining depth and coal floor water pressure [6]. According to the latest statistics from severe coal mine water accidents in China from 2000 to 2012, it is shown that mine water inrush accidents frequently occur, especially the coal floor water inrush accidents [7]. On no account can we ignore the immense danger of mine water accident, although the accidents times and death toll are decreasing from 2005 (Fig. 1).

The permeability behavior of the rock formations under coal floor is a key attribute in determining water inrush or not. Therefore, obtaining the hydraulic conductivity of the rock formations under floor will be proved to be a practical significance in coal extractions. In general, the hydraulic conductivity of rock can be measured by laboratory hydraulic tests using core samples [8–14] or field measurements, such as pumping tests and water injection tests [14–21]. Although laboratory tests are easy to perform and are repeatable, the values of rock formations are too heterogeneous and laboratory tests have difficulties in determining hydraulic conductivity accurately due to the complex field conditions. Conversely, field measurements can measure the hydraulic parameter directly and are useful and preferable for investigation of the permeability propagation behavior of rock formations under high water pressure. But the costs of the tests are fairly high, as well as the high technical requirements, and the field measurements are rarely used to measure the hydraulic parameter of the rock formations in coal mines.

In Eastern China, 18 coal seams of Permo-Carboniferous coal seams are named No. 1 to No. 18 coal from top to bottom, as well as the limestone. Baodian coal mine is situated in Yanzhou, Eastern China and is a large modern coal mine. It was formally put on production on June 10, 1986 and its production capacity is 3 million tons. Nowadays Baodian coal mine is mining the No. 3 coal, and will mine the deep No. 16 and No. 17 coal quickly with the decrease of the shallow coal. Floor water inrush threatens the deep coal production due to the close distance between the aquifers and the No. 16 and No. 17 coal. To obtain the hydraulic conductivity of the rock formations between the aquifers and the No. 16 and No. 17 coal for further evaluating the risk of floor water inrush, water injection tests were carried out at Baodian coal mine.

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2. Water injection tests

2.1. Water injection tests method

The hydraulic conductivity of the materials is measured in the boreholes by drilling two boreholes, in which one borehole is used to inject water and another borehole is used to monitor the change of water pressure. The water injection test method in this work is illustrated in Fig. 2. If we plan to measure the hydraulic conductivity of one rock formation with a depth from h_1 to h_2, then two boreholes are drilled to the depth of h_2; casing pipes are installed in the boreholes from the top to a depth of h_1, h_1 to h_2 which are bare holes. After that, a pressure measuring sensor is installed in the observation borehole to monitor data, and the sensor is connected with the pressure measuring instrument by cables. On the other hand, the injection borehole is connected with a pump. In addition, the flow meter and pressure gauge are fixed. Flanges are used to seal off the boreholes at last. It is conceivable that injecting water into the inject borehole puts a water pressure on the rock formation and has results in hydraulic fracturing in the rock mass.

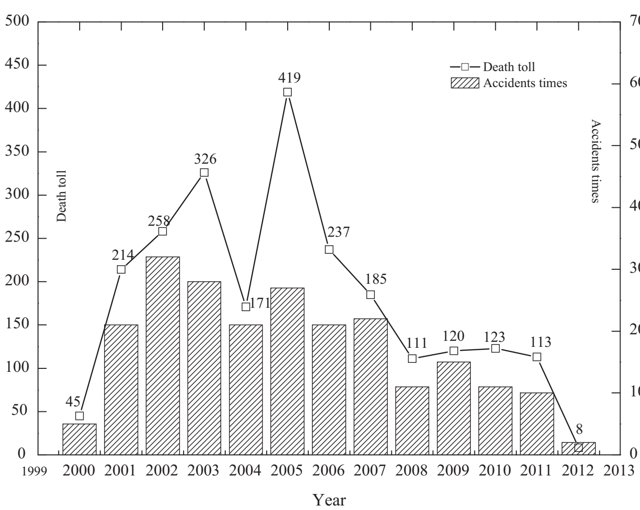

Fig. 1. Mine water accidents of China from 2000 to 2012.

2.2. Water injection tests Program

Our study is centered in the area between the No. 17 coal and No. 14 limestone aquifer, which consists mainly of mudstone, sandstone and limestone. We chose the connected area of track roadway of 14 mining area and southern inclined well of Baodian coal mine to carry out the injection tests (Fig. 3).

According to the drilling data, the distance between the No. 17 coal and No. 14 limestone ranges from 55 m to 65 m. Thus, three segments of rock formations were divided according to the boundary of No. 12 limestone, No. 13 limestone and No. 14 limestone. Therefore, four boreholes (Br-1, Br-2, Br-3 and Br-4) were drilled in this area to a depth of 25 m, 37 m, 51 m and 51 m, respectively. Four boreholes were all horizontal boreholes. Br-1, Br-2 and Br-3 are injection boreholes, while Br-4 is observation borehole. Injection boreholes and observation borehole are 3 m apart. The parameters of boreholes are presented in Table 1. The first test section is mainly mudstone and sandstone, while the second test section is mainly limestone and the third test second is mainly mudstone and sandstone, as shown in Fig. 4.

3. Mathematical model of Hydraulic conductivity

Hydraulic conductivity is calculated assuming a steady-state laminar flow rate in homogeneous and isotropic media around a test borehole [18]. In the case of a cylindrical well, the steady-state flow rate is governed by the Laplace equation:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial u}{\partial r}\right)+\frac{\partial^2 u}{\partial z^2}=0 \tag{1}$$

where u is the pressure of the pores and is represented by cylindrical coordinates (r, z).

However, analytical solution cannot be obtained for this equation. If it is assumed that the equal surfaces are semi-ellipsoids and flow rate lines are symmetrical with respect to a horizontal plane which goes through the midpoint of the cylindrical end [22,23], then

$$K=\frac{Q}{2\pi L H_0}\ln\left[\frac{L}{2r_w}+\sqrt{1+\left(\frac{L}{2r_w}\right)^2}\right] \tag{2}$$

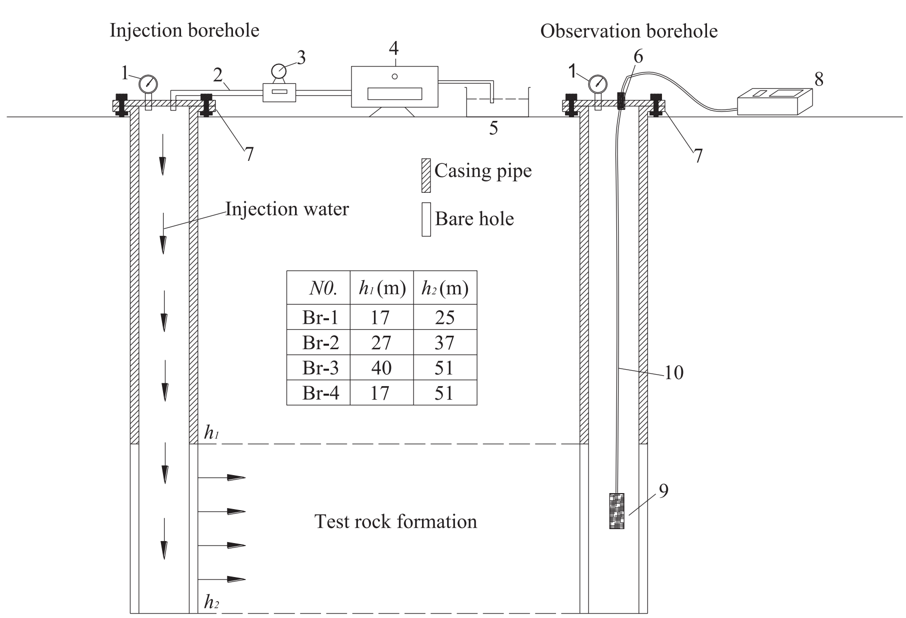

Fig. 2. Schematic system diagram of water injection tests method.