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Application of a non-linear viscoelastic-plastic rheological model of soft coal on borehole stability

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A B S T R A C T

Time dependent deformation of coal has a significant effect on the stability of underground structures. In this study, taking the visco-elastic–plastic characteristics and the damage effect into account, a non-linear model was proposed to describe the creep behavior of soft coal. Meanwhile, the creep equations of the proposed non-linear model were derived and the three-dimensional creep equations were constructed by generalizing the one-dimensional creep equations. At the same time, the uniaxial creep tests on soft coal specimens under different axial stress conditions were carried out to validate the proposed model. It is found that the present model can not only reproduce the transient creep under low axial stress level, but also can accurately predict the steady and accelerating creep stages under high axial stress level. Finally, borehole stability in soft coal seam was investigated based on the proposed model. The results show that the vertical displacement and plastic zone range around borehole gradually increase while the increasing rate decreases and tends to be stable after 20 days. It can also be obtained that the creep duration tends to be stable when it is about 20 days after drilling excavation under the simulation conditions. The analysis results should be useful for the long-term stability of boreholes in soft coal seam for gas extraction.

1. Introduction

The most commonly applied methane control solution, especially in high in-place gas content coal beds, is drilling methane drainage boreholes into the panel area prior to longwall mining to reduce the methane content of the coal bed. These boreholes can be vertical or horizontal boreholes drilled from the surface, or in-seam horizontal boreholes drilled from the underground entries (Karacan et al., 2011). On the other hand, an overwhelming majority of coal seams in Chinese coal mines took shape over a period of Carboniferous-Permian. As a consequence, the coal went through a number of strong tectonic movements and the original cracks in the coal mass were destroyed. The coal changed into a soft and construction–complex medium (Cheng et al., 2011; He et al., 2005). Creep of the boreholes is of critical importance because coal is a weaker material than sandstones and limestones, and the stress concentration around the boreholes may cause boreholes to fail easily, especially boreholes drilled in soft coal seam. These situations are more severe when the boreholes are completed open-hole (Haimson, 2007; Whittles et al., 2007; Karacan et al., 2007).

Time dependent deformation of rocks has a significant effect on stability of underground structures. In order to study the stability of the underground structures and designing their support system, time dependent deformations should be highly considered (Shalabi, 2004; Tsai et al., 2008). Therefore, time-dependent behavior of underground structures as well as predicting the long-term behavior is of great importance. Study of creep behavior in the field of rock has been done extensively in the literature, involving theoretical, experimental and numerical methods (Wang, 2004; Yang et al., 2014a,b; Sone and Zoback, 2014; Schoenball et al., 2014; Aubertin et al., 1991; Li and Xia, 2000; Hayhurst, 1972). But these studies are mostly carried out based on the triaxial creep tests in the laboratory. In general, the rheological behavior of rock is typically characteristic of the viscosity, elasticity and plasticity. Many creep models have been proposed by researchers to describe the visco-elasto-plastic rheological behavior. The classical Burgers

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and Nishihara models are widely adopted in practical engineering due to its simplicity (Cao et al., 2014; Malan, 1999). It is also well known that rock properties measurements based on laboratory tests cannot be directly extrapolated in field scale without due precaution (Coggan et al., 2013; Drescher and Handley, 2003). Because the mechanical properties of discontinuous rock mass strongly depend on the properties and geometry of joints. Therefore, it is essential to use numerical analysis for simulating time-dependent behavior of rock mass.

In this paper we develop a non-linear creep model of coal in which the damage effect at the stage of accelerating creep is taken into account. To validate the new model, uniaxial creep tests were carried out on raw coal specimens under different axial stress conditions. Besides, the numerical analysis code of nonlinear rheological model is investigated by the secondary development routine interface of software (FLAC3D), based on which the creep properties of borehole in soft coal seam were studied.

2. Experimental methodology and results

2.1. Experimental methodology

The studied soft coal specimen was selected from the Pingdingshan No.8 coal mine located in Henan Province of China, as shown in Fig. 1. To avoid the oxidation of coal, the material was jacketed with cling film immediately after it was cut down from the working face. All the tests were carried out on cylindrical specimens at room temperature. The target size of cylindrical specimens was 50 mm in diameter and 100 mm in height according to the international standard for rock mechanics tests, but the final size was slightly of discrepancy after carefully cutting and polishing as shown in Table 1. The chemical composition of coal is shown in Table 2.

All creep tests were conducted on the MTS815.02 rock servo controlled equipment at China University of Mining and Technology, as shown in Fig. 2. The MTS compression load capacity is 850 MPa for a standard cylindrical specimen. The internally mounted linear variable differential transformer (LVDT) provides a displacement indication of the actuator piston rod. The machine's LVDT on the vertical stroke of the hydraulic ram is used to measure the axial deformation of the specimen. Because of the actuator, the LVDT measures the total deformation of the specimen as well as the deformation of platens and loading crossbar frame. Following ASTM Standards-D7012, a suitable calibration for machine deformation was applied to the test data to get the true specimen axial strain values.

To investigate the creep behavior of coal under different axial stress conditions, the multi-step creep test scheme was adopted. The procedure of multi-step test could be described as follows. Firstly, an initial axial displacement loading was applied under a constant deformation rate of 0.02 mm/min until the designed axial stress level was achieved. After that, the stress was maintained at a constant level and the specimen was allowed to creep for an enough time interval until the deformation reached a quasi-steady state, during which the axial deformation was continuously monitored. Then, under the current axial stress level, the next loading step was applied with an increment of axial stress. Finally, with the increase of loading step the accelerated creep appeared and the coal failure took place. In this study, the designed axial stress level at the first loading step is 3.0 MPa and the increment of axial stress between each loading step is 1.0 MPa.

2.2. Experiment results

According to the multi-step creep test and the Boltzmann superposition principle, the stress–strain–time relationships of n loading steps obtained from one specimen are equivalent to n one step loadings on different specimens at corresponding stress levels. Three typical strain–time curves at different axial stress levels $\sigma_0 = 3.0$ MPa, 6.0 MPa and 12.0 MPa are shown in Fig. 3. For test

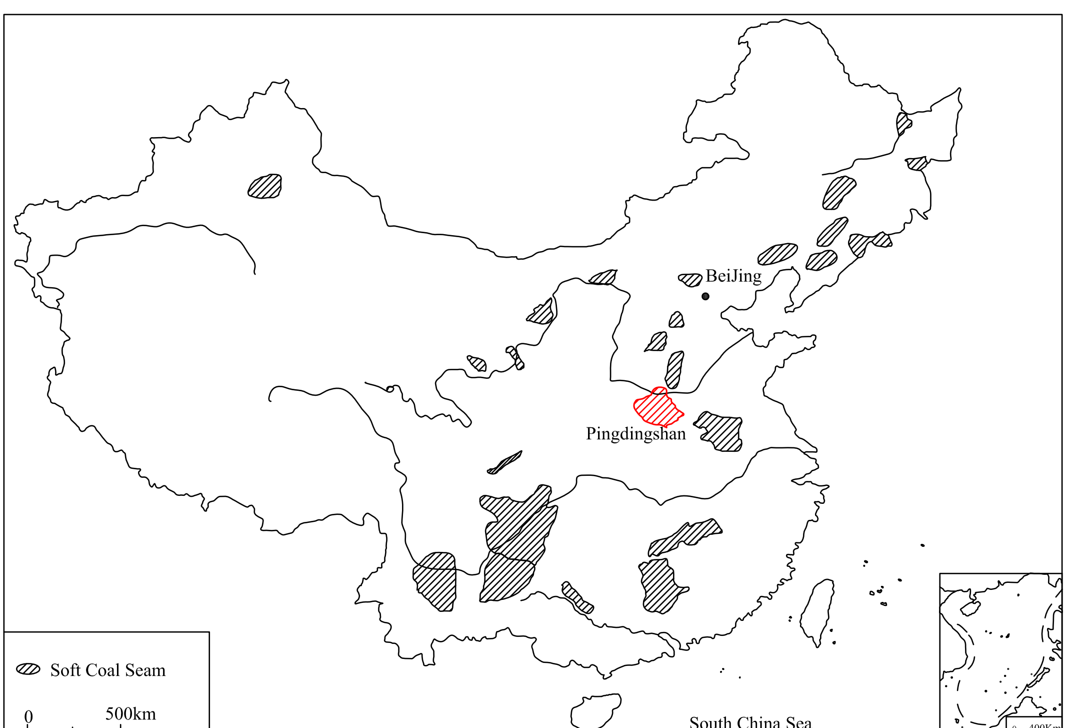

Fig. 1. Map showing location of the mine from which specimens were used.

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