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Numerical investigation of the scale effect and anisotropy in the strength and deformability of coal

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ABSTRACT

The decrease in strength and stiffness of coal with increase in specimen size has long been recognized as scale effect. In this study, a synthetic rock mass (SRM) approach has been used to investigate this scale effect and the anisotropy of coal. A discrete fracture network (DFN) for the coal was created and then embedded into bonded-particle models to form a range of varying size of SRM coal specimens. Unconfined compression tests on the SRM specimens showed that the SRM approach is capable of quantitatively reproducing the dependency of the strength and stiffness on the size of the coal specimens. The strength and stiffness anisotropy of coal can also be reproduced. The numerical results are shown to be in good agreement with published laboratory and field test results.

1. Introduction

Determination of the in-situ strength and stiffness characteristics of coal is essential for roadway support, top coal cavability, and pillar design. The typical method of estimating the strength and stiffness of a rock is through preparation of rock specimens and then performing laboratory and field tests. For coal, however, it is very difficult to obtain intact specimens of the required size for testing. Borehole core specimens are usually available during exploration but are rarely available after the start of production (St George, 1997). Furthermore, coal specimens usually deteriorate rapidly after they are removed from the mine due to the temperature and humidity changes (Bieniawski, 1968a). Laboratory and field tests on coal have shown the importance of scale effects with a significant decrease in strength and stiffness with increasing specimen size (Bieniawski, 1968a, 1968b; Deisman et al., 2010; Medhurst and Brown, 1998; Vanheerden, 1975; Wagner, 1974), see Fig. 1. The strength decrease rate diminishes significantly above a certain scale, which is referred to as the representative elementary volume (REV) (Cunha, 1990). Field tests have indicated that the REV of coal is approximately 1.5 m (Bieniawski, 1968a, 1968b; Vanheerden, 1975). This scale effect has been attributed to the various discontinuities observed within the coal, including cracks, bedding planes and butt and face cleats (Bieniawski, 1968b; St George, 1997). Discontinuities within coal result in an anisotropic fabric with varying strength and stiffness properties in relation to the orientation of the loading direction (Okubo et al., 2006; Pomeroy et al., 1971; Szwilski, 1984).

Field strength/deformation properties for numerical modelling are often estimated based on rock mass/intact rock characteristics and the use of rock mass classification systems such as the Q Index (Barton et al., 1974), the rock mass rating (RMR) system (Bieniawski, 1976) and the Geological Strength Index (GSI) (Hoek et al., 1998, 2000). The GSI, integrated with the Hoek–Brown failure criterion is commonly used for estimating rock mass properties (Cai et al., 2004; Hoek and Brown, 1997; Zhang, 2010). The GSI was primarily developed for hard rocks, with modified GSI charts being developed and used for poor and weak rock masses (Hoek et al., 1998; Osgoui et al., 2010). Medhurst and Brown (1998) adopted the generalised Hoek–Brown criterion to scale parameters of intact coal to in situ peak strength parameters. Deisman et al. (2010) also used the GSI to characterize the mechanical properties of a coal seam reservoir and suggested that the GSI is able to represent the influence of scale effects on coal strength. Esterhuizen (1998) stated that the GSI can be used to estimate the strength of large scaled coal. Saroglou and Tsiambaos (2008) modified the Hoek–Brown criterion in order to allow for the effect of strength anisotropy.

The synthetic rock mass (SRM) method has been recently developed to quantitatively investigate the effect of discontinuities on the mechanical behaviour of a rock mass (Pierce et al., 2007). The SRM approach employs a discrete fracture network (DFN) superimposed upon a bonded particle model (BMP) to represent a jointed rock mass. Through DFN simulation, the structure of an in-situ jointed rock mass can be explicitly represented. A DFN can be generated from measured in situ joint data

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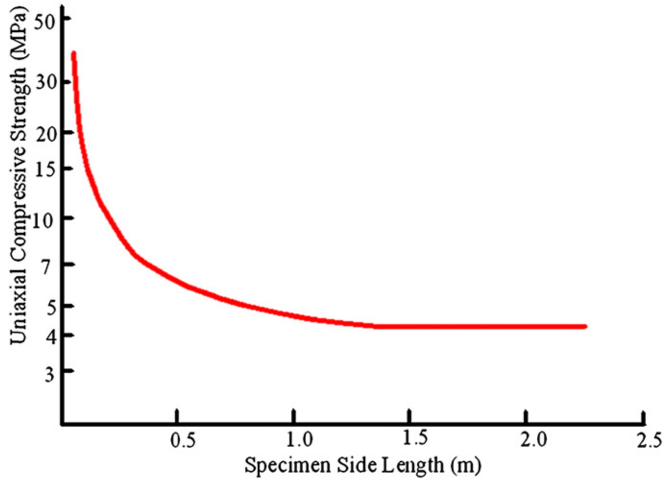

Fig. 1. The effect of specimen size on the strength of coal. (Modified after Bieniawski, 1968b)

obtained from a range of sources including borehole logging and underground and surface outcrop/excavation mapping using windows and scanlines. Both conventional field mapping and remote sensing (Terrestrial LiDAR and photogrammetry) methods have been used for characterizing the geometry of DFN within coal. By testing the SRM specimens, the failure mechanisms of rock mass can be observed in detail and mechanical properties such as the strength, stiffness and brittleness of a rock mass can be estimated. The SRM approach has been successfully utilized for evaluating rock mass mechanical properties of site specific cases (Brzovic et al., 2014; Cundall et al., 2008; Esmaieli et al., 2010; Grenon et al., 2014; Mas Ivars et al., 2011; Pettitt et al., 2011; Pierce et al., 2007; Vallejos et al., 2013; Vallejos et al., 2014; Zhang et al., 2011), and also the effects of pre-existing discontinuities on rock mass behaviour (Bahaaddini et al., 2013; Chiu et al., 2013; Lambert and Coll, 2014; Pan et al., 2014; Scholtès and Donzé, 2012). For Coal Measures, Deisman et al. (2010) used the SRM approach to investigate the effects of fractures or joints on the geomechanical properties of coal and showed that the SRM method is capable of simulating the strength and deformation of a coal seam. Poulsen and Adhikary (2013) recently investigated the scale effect of coal by incorporating random distribution of defects in a bonded particle model.

In our study we use the SRM approach to investigate both the scale effect and the anisotropy in strength and stiffness of coal at the Wuyang coal mine, China. SRM coal specimens were created by incorporating the DFNs into bonded particle models (BPMs) and then loaded in unconfined compression.

Table 1
Spacing and length of bedding planes, face cleats and butt cleats used in the DFN generation.

Discontinuity type	Length (cm)	Std. dev. (cm)	Spacing (cm)	Std. dev. (cm)
Bedding planes	200	0	10	0
Face cleats	200	40	8	1
Butt cleats	20	4	8	1

2. Model setup

2.1. The coal discrete fracture network

In a coal seam, there are typically three discontinuity sets: bedding planes, face cleats and butt cleats (Fig. 2). Bedding planes are typically sub-horizontal with a very high persistence on a scale of tens of metres (Seedsman, 2001). Face cleats which generally formed first and butt cleats are mutually orthogonal and also perpendicular to bedding planes (Laubach et al., 1998). Butt cleats generally terminate at face cleats, see Fig. 2B (Dawson and Esterle, 2010). The spacing of the bedding planes can range from a scale of millimetres to tens of centimetres (Laubach et al., 1998). Cleat spacing is found to have a linear relationship with bed thickness (Law, 1993) and varies with ash content and coal type. Coals with low ash content tend to have smaller cleat spacing than those with high ash contents (Laubach et al., 1998). Bright coal generally has a smaller cleat spacing than dull coal (Dawson and Esterle, 2010; Laubach et al., 1998).

In this study, a coal discrete fracture network with a volume equal to a cube of edge-length 2 m was generated using the FracMan code (Dershowitz et al., 1996). The spacing and length of bedding planes, face cleats and butt cleats are given in Table 1. These parameters are estimated based on longwall mapping and borehole televiewer imaging at the Wuyang coal mine. The generated DFN is shown in Fig. 3.

2.2. Intact coal properties

Borehole in-situ strength tests were carried out in a coal roadway at the Wuyang coal mine in order to measure the coal strength, see Fig. 4A. A 56-mm-diameter 10-m-length borehole was drilled horizontally into the roadway wall. A rod with a probe fastened to the top was then inserted into the borehole. The probe was connected to a high pressure pump with a pipe. The borehole probe is jacked against the borehole

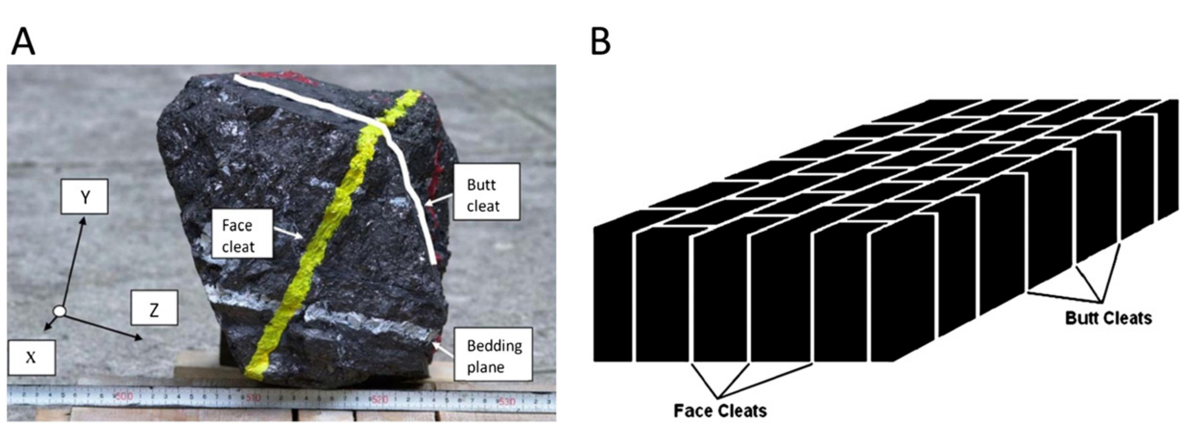

Fig. 2. (A) Block specimen of coal showing bedding plane, face cleat and butt cleat (Okubo et al., 2006), and (B) schematic plot of face and butt cleats in coal (Dawson and Esterle, 2010).