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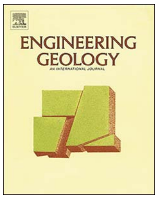

Simulating mining-induced strata permeability changes

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ABSTRACT

Mining processes fracture the surrounding strata and may modify the flow of groundwater by inducing new fractures or changing the permeability of existing defects. The result of mining-induced permeability changes can be disturbance to aquifers or other surface or sub-surface water bodies. Traditional methods for predicting mining-induced fracture connectivity and enhanced permeability based on empirical strain-based criteria may not satisfy modern regulatory demands, nor adequately reflect local geological, geotechnical and hydrogeological conditions. Standard continuum numerical methods may indirectly estimate permeability enhancement from plastic strains however they are not able to track aperture on flow paths or predict fracture connectivity. This paper presents a numerical approach that is demonstrated to be capable of representing longwall mining induced fracturing in sedimentary rock masses. By initiating and propagating fractures, determining connectivity and calculating aperture in a piecewise manner on flow paths, we have estimated permeability enhancement from first principles. Fracture intensity and porosity metrics are calculated and identify the height of the enhanced permeability fractured zone above a longwall goaf. Permeability within the overburden is estimated from the Kozeny-Carman permeability–porosity equation. At a mine site studied in detail in this paper a permeability increase from the in situ state is predicted to range from approximately eight orders-of-magnitude in the caved zone to one to two orders-of-magnitude in the strata above the fractured zone. Realistically simulating cracking, fracturing and crushing of rock strata remains numerically intensive and challenging at the scale of a longwall panel. It is demonstrated in this paper and provides valuable insights into the rockmass response to mining.

1. Introduction

Mining's license to operate is increasingly reliant on reducing unanticipated impacts on groundwater. Adverse impacts on aquifers, surface and sub-surface water is a growing community concern that necessitates advanced predictive tools for assessing mining-induced permeability enhancement. Traditional estimates for predicting fracture connectivity based on empirical strain-based criteria may not satisfy modern regulatory demands, nor adequately reflect local geological, geotechnical and hydrogeological conditions.

Regulatory strain limits for coal mining in sedimentary rock masses reported by Garritty (1983) range from 5 mm/m in Chile to 10 mm/m in the United Kingdom, while Tammetta (2013) refers to a 3 mm/m strain limit in India. A stacked layer of rock beams as an analogue of sedimentary strata is made by several authors (Muhlhaus, 1993; Khanal et al., 2012; Seedsman, 2013) and these strain limits can be considered with the use of beam theory. From simple beam theory, it can be shown that this range of strains can be achieved at the failure limit for span S to thickness t ratios of 5:1 to 10:1 largely independent of boundary conditions. For S/t ratios greater than 10:1, the collapse limit of 0.25 times beam thickness identified by Diederichs and Kaiser (1999) can be achieved at lower strains.

These ‘rule-of-thumb’ observations may not be sufficient when attempting to quantify mining impacts for modern day environmental statements. Current regulations require greater accuracy with reduced uncertainty for mine-site specific geological settings.

Continuum numerical methods may estimate permeability changes indirectly from plastic strain however plastic strain is in itself is a user-defined artefact of the material yield function and can be strongly impacted by mesh size, softening rates, and boundary conditions, for example. Continuum methods are also unable to track aperture along flow paths or determine fracture connectivity.

In this paper we outline the use of a discrete element particle code (Potyondy and Cundall, 2004; Potyondy, 2012; Poulsen and Adhikary, 2013; Scholtes and Donze, 2013) to initiate and propagate fractures, determine aperture in a piece-wise manner on fracture paths and determine fracture connectivity. While particle codes are not new in geomechanics their use is typically applied on small-scale homogenous

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samples simulating laboratory rock tests. For simulation of a sedimentary rock mass at the scale of a longwall panel in cross-section, it is necessary to represent a high variability in material stiffness and strength, install representative in situ stresses and realistically represent the mining process of material excavation.

The theory of discrete element particle codes is not presented in this paper as it is outlined at some length in the above-mentioned references; rather this paper concentrates on the practical aspects of large scale simulations involving the initiation and propagation of fractures through heterogeneous media. To that end, in this paper, we concentrate on demonstrating that the fracture initiation stress and propagation and termination path agrees with theory. We then outline the modelling aspects involved in representing the high material variability of a sedimentary rockmass. Before simulating a real-world problem, we outline the development of a tool set used for the specific purpose of estimating permeability enhancement from first principles.

In this paper beam theory is used to demonstrate the numerical approach as the fracture initiation stress can be predicted by theory. While the predicted fracture initiation stress and stability deflection are in good agreement with beam theory (Diederichs and Kaiser, 1999), fracture initiation and propagation is of the most interest to this work. For a beam with distributed load, fractures initiate at the abutments, propagate normal to minimum principle compressive stress σ_3 and then follow the limit of the force arch tangential to the maximum compressive stress σ_1, stabilising at a σ_3/σ_1 ratio of approximately 0.2 when mode 1 fracturing is halted (Hoek and Martin, 2014). With sufficient load, additional fractures initiate mid-beam and again terminate, turn or bifurcate at the force arch. Additional observations pertinent to aperture and permeability are evident from the simple beam model discussed in Section 2.

Various metrics from the numerical model and how these relate to permeability are presented and discussed in Section 3. Section 4 outlines practical considerations for large-scale simulations in mining, while a practical example is discussed in Section 5. In a full-scale longwall study, we applied the tool at two well-studied mine sites that have been previously examined with continuum methods with full details reported in Adhikary et al., 2017. Selected results from one of these mines presented in this paper demonstrate that the evolved fracture pattern provides unique insights into permeability enhancements that correspond well with mine observational data.

2. Fracture initiation and propagation in a bonded-particle model

Bonded-particle models (BPMs) are well described in the literature. They have been shown to evolve strength and deformation characteristics of sedimentary rocks and coal from simple interactions of many incompressible elements (Potyondy and Cundall, 2004; Potyondy, 2012; Poulsen and Adhikary, 2013; Scholtes and Donze, 2013).

Following the approach of Poulsen and Adhikary (2013), a calibrated BPM was formed using the PFC 'flat joint' model (Potyondy, 2012; Poulsen and Adhikary, 2013; Scholtes and Donze, 2013) for particle-to-particle interaction that achieves typical tensile strength (TS) to unconfined compressive strength (UCS) ratios representative of rock (5–20%). This model of 0.1 m width, 0.2 m height contained 906 particles with approximately 20 particles on the minimum dimension. Each particle-to-particle contact has the default number of "flat joints" (4) resulting in a highly linear response to peak strength. Applied boundary velocities were sufficient to simulate quasi-static loading. With the properties presented in Tables 1 and 2, the sample simulates a material with UCS of 11.0 MPa, TS of 1.1 MPa and Young's modulus of 8.38 GPa. In these basic calibration studies the strength and deformation characteristics were obtained from simulated unconfined compression and direct tension models (Fig. 1).

Table 1
Microparticle properties for beam study.

R_{min}	2.0 mm	E' (bond modulus)	5.5 GPa
R_{max}	3.0 mm	k_n/k_s	0.5
μ	0.05	Unit weight[a]	2236 kg/m^3

R = particle radius, k_n and k_s = normal and shear inter-particle stiffness, μ = target porosity.

[a] From resultant porosity and particle density.

Table 2
Bond properties for beam bonded-particle model.

FJM nseg	6	FJM cohesion	5.8 MPa
FJM E	5.5 Gpa	FJM tensile strength	1.2 MPa
FJM k_n/k_s	0.5	FJM friction angle	33°

FJM = flat joint model, nseg = number of segments, E = bond modulus, k_n and k_s = normal and shear bond stiffness.

3. Theoretical verification

In this paper, the approach of other authors (Muhlhaus, 1993; Khanal et al., 2012; Seedsman, 2013) was followed, considering sedimentary rock masses as a layered series of rock beams. Therefore, for calibration of the numerical model, a beam with uniform distributed load was simulated and results compared with simple beam theory and the Voussoir beam analogue (Diederichs and Kaiser, 1999). The Voussoir analogue is widely used in mining geomechanics for stability studies of coal roadways and caving studies of longwall mining (Brady and Brown, 1993).

Diederichs and Kaiser, 1999 discuss how the boundary conditions for a Voussoir beam can be self-generating when abutment fractures initiate and propagate under self-weight to form the equivalent of the natural jointing assumed for a Voussoir beam (Fig. 2). A numerical tool that can simulate this evolution of boundary conditions by formation of subvertical fractures has unique advantages for mining overburden studies. Diederichs and Kaiser's paper and the simulation below suggest that the strength and deformation characteristics for this type of evolving beam are equivalent to a pre-fractured Voussoir beam.

A 1 m beam with S/t ratio of 10:1 of approximately 20 particles in the minimal dimension was constructed with interparticle properties outlined in Table 1 and Table 2. Particles representing the beam's boundary were velocity constrained to simulate fixed boundary conditions. In this and all subsequent numerical models, the code PFC by Itasca Consulting group was used (ITASCA, 2014).

A uniform distributed load was applied to the beam from increasing self-weight by gradually increasing gravitational acceleration. From simple beam theory, boundary stresses should exceed this beam's TS at approximately 96 m/s^2. With increasing self-weight, mid-span stresses should exceed strength and the beam should stabilise. With self-weight achieved from a gravitational load with acceleration of 110 m/s^2, abutment fractures should initiate, propagate then stabilise, while the mid-span fracture should likewise initiate, propagate then stabilise. For both abutment and mid-span fractures, propagation should cease when stresses at the crack tip prevent ongoing mode 1 failure. By the estimate outlined in Diederichs and Kaiser, 1999, with self-weight from an acceleration of 110 m/s^2, the final deflection should be approximately 0.27 mm and, with increasing self-weight, failure of the beam should occur with snap-through/crushing failure when the maximum beam deflections approach 25 mm.

Fig. 3 highlights aspects of fracturing, deflections and the force arch as the beam was loaded to failure. A gravitational acceleration of 110 m/s^2 was initially applied in the model. In addition to matching the fracture initiation stress, the model demonstrates the fracture path following the normal to σ_1 and terminating when the σ_3/σ_1 ratio