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Parametric study and dimensional analysis on prescribed hydraulic fractures in cave mining

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ABSTRACT

Cave mining has become a popular underground mass mining method and extends its applications to more component orebodies at depths. To ensure continuous cave propagation, effective pre-conditioning of the orebody to improve its caveability and fragmentation sizes is essential. Hydraulic fracturing has been used as a pre-conditioning method in cave mining by creating artificial fractures in the orebody. In a previous study, the requirement for creating orientation-controllable hydraulic fractures was established and the concept of prescribed hydraulic fracturing was proposed to fill this research gap. The deep understanding of how various factors and their combinations impact prescribed hydraulic fracture propagation is important for the successful application of this newly developed pre-conditioning strategy. In this paper, the concept of dimensional analysis is employed to reduce the number of independent variables governing the approach from 19 to 10 following their identification. A procedure is also developed using the concept to project laboratory scale numerical modelling results to field scale in the absence of actual field trials.

1. Introduction

Cave mining, which refers to block caving or panel caving in this paper, is an underground mass mining system for the extraction of large, low-grade orebodies that are at unfavourable depths for open pit mining and are uneconomic to mine with other underground mining systems. This mining system is traditionally applied to weak orebodies that satisfy other requirements detailed in Hartman and Mutmansky (2002) and Hustrulid and Bullock (2001). The Laubscher Rules (Laubscher, 1994) govern the design of cave mines.

In the last decade, cave mining has been applied to orebodies outside its traditionally prescribed orebody characteristics as it is now taking place at depths of up to 2 km below the surface and in competent orebodies. Cave mining, provided the orebody is suitable, is the lowest operating cost mining system compared to any other underground mining system. Chitombo (2010) summarized the evolution of cave mining and stated that this mining system is moving from the conventionally relatively small cave size towards the cave size that could be described as 'super caves' in which cave heights of 500–550 m will be used.

In cave mining at depth and/or in competent orebodies, effective pre-conditioning of the orebody is essential to achieving successful caving. Re-activation of stalled caving also requires artificially weakening the rock mass or decreasing large block sizes to reduce the risk of arching that hinders continuous cave propagation (Laubscher, 2000). Thus, pre-conditioning is required to modify the quality of the orebody to enable it to cave continuously under gravity with desired fragmentation sizes. The essence of hydraulic fracturing as applied in cave mining is to induce artificial fractures in the orebody. Compared with other pre-conditioning methods, such as blasting, hydraulic fracturing is extremely cost effective and is more commonly used (Chitombo, 2010).

Hydraulic fracturing emerged from the oil industry and realized its first successful commercial application in 1949 (Clark, 1949). It was first introduced into the mining industry in coal mining for gas drainage (Puri et al., 1991; Wright et al., 1995; Zhai et al., 2012), hard roof control (Chernov, 1982; Fan et al., 2012; Jeffrey et al., 2013; Jeffrey and Mills, 2000; Jeffrey et al., 2001; Lekontsev and Sazhin, 2014; Zhai et al., 2012) and enhancing top coal caveability in longwall top coal caving (Huang et al., 2011; Huang et al., 2015). The application of hydraulic fracturing has since been extended to cave mining for either caving re-activation or pre-conditioning (Araneda et al., 2007; Catalan et al., 2012; He et al., 2015; Jeffrey, 2000; Van As and Jeffrey, 2000a, 2000b; van As et al., 2004).

He et al. (2016a) provided a comprehensive review of hydraulic fracturing and traced its origin from the oil and gas industry to its first

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Nomenclature

List of Symbols

σ	the stress, MPa
σ_1	the maximum principal stress, MPa
σ_2	the intermediate principal stress, MPa
σ_3	the minimum principal stress, MPa
σ_n	the net pressure, MPa
σ_c	rock UCS, MPa
σ_T	rock tensile strength, MPa
θ_{BD}	the borehole dip angle, °
θ_{BS}	the borehole strike angle, °
θ_P	the perforation angle, °
D	the borehole diameter, m
$\mathscr{D}$	the dimensionless borehole diameter
E	Young's modulus, MPa
F	the geometric factor
g	gravitational acceleration, m/s^2
H	the pre-located fracture spacing, m
l	the hydraulic fracture half-length, m
l_P	perforation length, m
L_h	horizontal length of the PHF, m
L_v	vertical length of the PHF, m
L_{hu}	horizontal length of the PHF upper strand, m
L_{vu}	vertical length of the PHF upper strand, m
L_{hl}	horizontal length of the PHF lower strand, m
L_{vl}	vertical length of the PHF lower strand, m
$\mathscr{L}_{hu}$	the dimensionless PHF upper strand horizontal length
$\mathscr{L}_{vu}$	the dimensionless PHF upper strand vertical length
$\mathscr{L}_{hl}$	the dimensionless PHF lower strand horizontal length
$\mathscr{L}_{vl}$	the dimensionless PHF lower strand vertical length
m	homogeneity index
N_P	the number of the final dimensionless factors
N_V	the number of factors involved before dimensional analysis
N_d	the number of fundamental dimensions
$\mathscr{N}$	the dimensionless net pressure
k	hydraulic conductivity, m/s
k^*	material permeability, m^2
$\mathscr{K}$	the dimensionless rock permeability
K_{Ic}	rock toughness, Pa $m^{1/2}$
ρ	fluid density, kg/m^3
p	pore pressure, MPa
Q	the flow rate, m^3/s
r	the hydraulic fracture radius, m
R_{DM}	the rank of the dimensional matrix
	the dimensionless pre-located fracture radius
$\mathscr{S}$	the dimensionless differential stress
t	injection time, s
$\mathscr{T}$	the dimensionless rock tensile strength
μ	fluid viscosity, Pa s
ν	the Poisson's ratio
w	the pre-located fracture maximum width, m

application in mining in coal gas drainage before it being adopted in cave mining practice. Theoretically, the hydraulic fracture (HF) propagation path is controlled by and is perpendicular to the minimum principal stress (σ_3) orientation (Hubbert and Willis, 1972).

Current hydraulic fracturing operations are designed based on the understanding that HFs have fixed orientations dictated by the direction of the minimum in-situ principal stress. Based on this understanding, the orientation of induced fractures from hydraulic fracturing is irrelevant in pre-conditioning of the orebody through HFs. However, this assumption might be problematic in situations where the existing natural fractures (NFs) are not oblique to the induced HFs to create intersections with the former but rather sub-parallel to them. The latter will not result in a blocky rock mass that is required for caving.

To achieve effective pre-conditioning, a hydraulically fractured blocky orebody is necessary and desirable, which implies that the relative orientations of the created HFs to the existing NFs are important (He et al., 2016a). He et al. (2016a) stated that the pre-conditioning efficiency of the conventional hydraulic fracturing practice in which orientation of the hydraulically induced fractures is dictated by the orientation of the minimum in-situ principal stress is limited if the orebody rock mass contains no dominant NFs or is dominated by NFs that are also perpendicular to the in-situ σ_3 orientation. In either of these scenarios, no blocky orebody is created based on the theoretically predicted orientations of HFs. Hence, HFs with controllable orientations are required so that effective pre-conditioning can be achieved in various geotechnical conditions. Effective hydraulic fracturing here implies a process in which the HFs form an additional joint set rather than merely increasing the frequency of an existing joint set.

There is a knowledge gap in creating HFs with controllable orientations to achieve blocky rock masses and desired fragmentation sizes. To ensure that HFs result in additional joint sets in a rock mass, He et al. (2016a) proposed the concept of prescribed hydraulic fracturing and concluded that prescribed hydraulic fractures (PHFs) with controllable orientations could be achieved if the stress shadow effect (Fisher et al., 2004) due to the existing fractures is properly utilized in combination with directional hydraulic fracturing (DHF) practice (He et al., 2016c). He et al. (2016b) provide proof of concepts for the proposed approaches for creating PHFs in which HF orientations are effectively independent of the minimum in-situ principal stress orientation. More details of prescribed hydraulic fracturing, including the need, can be found in He et al. (2016a).

To design a proper strategy for creating PHFs at a specific site in each geotechnical condition, the understanding of the effects of various factors on the PHF trajectory is critical. Various factors affecting the trajectories of PHFs are evidenced in He et al. (2016b). Therefore, to effectively manage the orientation of PHFs, which is critical for the successful application of the proposed strategies, the sensitivity of the trajectory orientations to these factors must be well understood.

In this paper, the influence of various factors on the creation of PHFs is studied to improve the understanding of this newly developed pre-conditioning method. First, factors having influence on prescribed hydraulic fracturing are identified and verified. Second, the effects of the identified factors influencing HF re-orientation that affects the creation of PHFs are investigated in a parametric study through numerical simulations using a numerical modelling code called Realistic Failure Process Analysis (RFPA). Finally, dimensional analysis is conducted to examine the potential extrapolation of laboratory-scale numerical modelling results to field-scale prototypes. The novelty in the paper is in determining how much influence each factor affecting PHFs has on the PHF trajectory to enable its effective management and in the use of the dimensional analysis to project laboratory scale numerical modelling results to the field scale. These objectives differ from previously published works by the authors that focused on identifying gaps in the literature He et al. (2016a) in how hydraulic fracturing is applied in cave mining and developing strategies for effective hydraulic fracturing in cave mining (He et al., 2016b; He et al., 2017).

2. Identification of factors affecting prescribed hydraulic fracturing

Factors affecting the re-orientation of HFs must be well understood and managed in the creation of PHFs in order for the approaches