International Journal of Rock Mechanics & Mining Sciences 91 (2017) 179–194

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Effect of discontinuity stress shadows on hydraulic fracture re-orientation

Qingyuan He[a], Fidelis T. Suorineni[a,*], Tianhui Ma[b], Joung Oh[a]

[a] School of Mining Engineering, Faculty of Engineering, University of New South Wales, Sydney, Australia
[b] State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, China

ARTICLE INFO

Keywords:
Hydraulic fracture re-orientation
Stress shadow effect
Differential stress
Rock mass homogeneity, Numerical modelling

ABSTRACT

Hydraulic fracturing has been applied to the cave mining industry as a pre-conditioning method to improve rock mass caveability and fragmentation sizes. In theory, the hydraulic fracture orientation is dictated by and is perpendicular to the minimum in-situ stress orientation. Such orientations will not always result in the creation of a blocky rock mass to aid caveability. The understanding of hydraulic fracture re-orientation induced by the stress shadow effect is important for either avoiding the undesirable interaction between multiple transverse hydraulic fractures or taking advantage of this phenomenon to create prescribed hydraulic fractures that result in the creation of blocky rock masses. In this paper, the existing knowledge of the stress shadow effect around a pre-existing discontinuity is reviewed. A 3D numerical modelling code, Rock Failure Process Analysis (RFPA) is used to investigate factors influencing hydraulic fracture re-orientation. It is established that hydraulic fractures can be forced to propagate in desired directions if advantage is taken of the stress shadow effect in combination with knowledge of rock mass homogeneity and site far field stress conditions. Both the differential stresses between σ_2 and σ_3 and between σ_1 and σ_3 affect the hydraulic fracture re-orientation geometry. The minimum far field stress magnitude has no direct impact on hydraulic fracture re-orientation. Rock mass homogeneity significantly influences how far a hydraulic fracture propagates along its predefined orientation from its initiation point before re-orientation.

1. Introduction

1.1. Background

Hydraulic fracturing originated from the oil and gas industry [1] and was introduced into the mining industry for different applications. Initially, it was applied to coal mining for improving coal seam permeability,[2–4] hard rock roof control [5–9] and enhancing top coal caveability.[10,11] Currently, it is being used in cave mining for reactivating stalled caves and pre-conditioning in block caving mining.[12–17]

As a pre-conditioning method, hydraulic fracturing is more cost effective compared with traditional blasting [18] and has the ability to improve both rock mass caveability and fragmentation sizes.[15] In practice, hydraulic fracturing boreholes are drilled from the surface or subsurface excavations into the targeted orebody to create multiple transverse hydraulic fractures (HFs) along them as additional fractures.

In a previous study, He et al.[19] summarized the state of the art of hydraulic fracturing in cave mining and identified a limitation in its current applications. In essence, the objective of hydraulic fracturing in an orebody is to make the orebody blocky so that it can cave continuously with desirable fragmentation sizes. This means the orientations of the created hydraulic fractures relative to the natural fractures (NFs) are essential to successful pre-conditioning. In the creation of a blocky rock mass, hydraulic fractures that result in a new independent joint set are preferable to that just simply increasing the frequency of an existing joint set.

According to the existing knowledge, hydraulic fracture orientation is dictated by and is perpendicular to the minimum in-situ principal stress (σ_3) orientation. In field applications, hydraulic fracturing operations are designed based on this principle to create hydraulic fractures. In some geotechnical conditions, the pre-conditioning hydraulic fractures are ineffective in generating a blocky rock mass that can cave under gravity. For example, at most caving mine sites in Australia where the σ_3 orientation is vertical and will favour the creation of horizontal hydraulic fractures, if the targeted orebody has no dominant natural fractures (Fig. 1a) or is dominated by horizontal natural fractures (Fig. 1b), the created hydraulic fractures will not be an independent joint set that can turn the orebody into a blocky one. Therefore, a means of creating hydraulic fractures that form an additional joint set to the existing natural fractures is desirable in such cases. Hence, hydraulic fractures with arbitrary orientations

* Corresponding author.
E-mail address: f.suorineni@unsw.edu.au (F.T. Suorineni).

http://dx.doi.org/10.1016/j.ijrmms.2016.11.021
Received 14 January 2016; Received in revised form 18 November 2016; Accepted 23 November 2016
1365-1609/

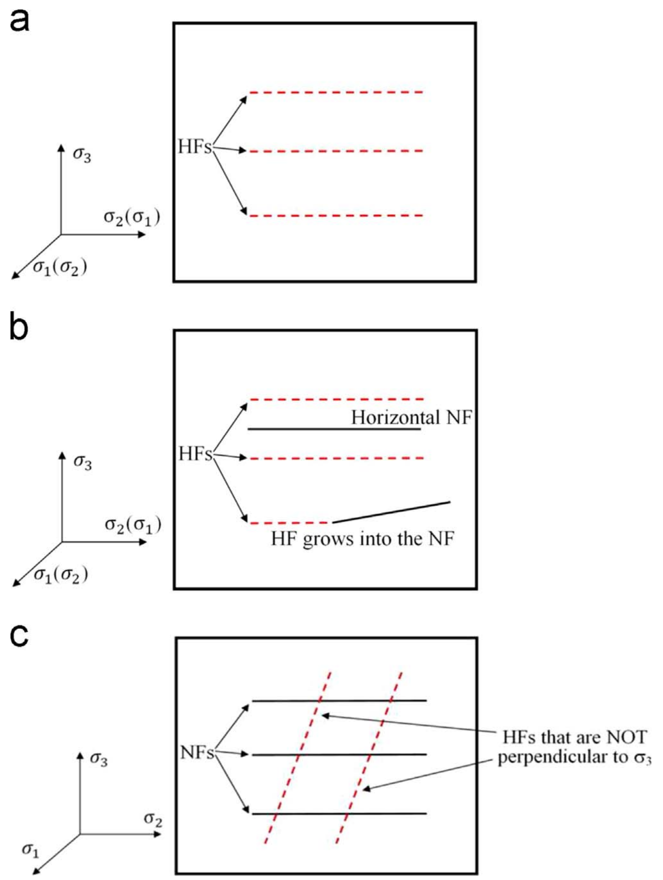

Fig. 1. Effectiveness of traditional hydraulic fracturing and prescribed hydraulic fracturing.[19] (a) traditional hydraulic fracturing in an orebody without dominant NFs; (b) traditional hydraulic fracturing in a mining block containing horizontal NFs; (c) a blocky orebody is created by prescribed hydraulic fracturing.

independent of the σ_3 orientation, are required. Hydraulic fractures with controllable orientations are here termed 'prescribed hydraulic fractures' (PHFs) (Fig. 1c).

To fulfil the task of creating PHFs requires a novelty in hydraulic fracture re-orientation against its theoretically predicted direction. It is hypothesized that creating PHFs is possible if factors that result in the re-orientation of hydraulic fractures are identified, studied and combined with directional hydraulic fracturing practice. Further details of strategies for creating PHFs can be found in [19].

Stress shadows [20–22] due to pre-existing fractures are known to cause re-orientation of hydraulic fractures against their theoretically predicted directions (Fig. 2). Fig. 2a illustrates a stress shadow from an isolated existing fracture. Fig. 2b shows how a hydraulic fracture created in the stress shadow is re-orientated from its theoretical direction due to the stress shadow effect. If more than one pre-existing fracture is present, two scenarios may be created depending on the distance between the pre-existing fractures. The first scenario occurs when the two fractures are close enough to have their stress shadows overlapping as shown in Fig. 3a. If the distance between these fractures is far enough, their stress shadows will not overlap and therefore resulting in their stress shadows being independent of each other with a stress shadow free zone between them as shown in Fig. 3b.

The stress shadow effect in the creation of re-oriented hydraulic fractures is explained as follows. First, we assume that the difference between σ_3 and σ_2 is less than that between σ_3 and σ_1 and therefore will govern the behaviour of the hydraulic fracture. In Fig. 2a, f_2 and f_3 represent the fracture-induced stresses (from the deformation of the fracture surfaces due to an internal proppant or fluid pressure acting against the far field stresses) pointing towards the far field σ_2 and σ_3

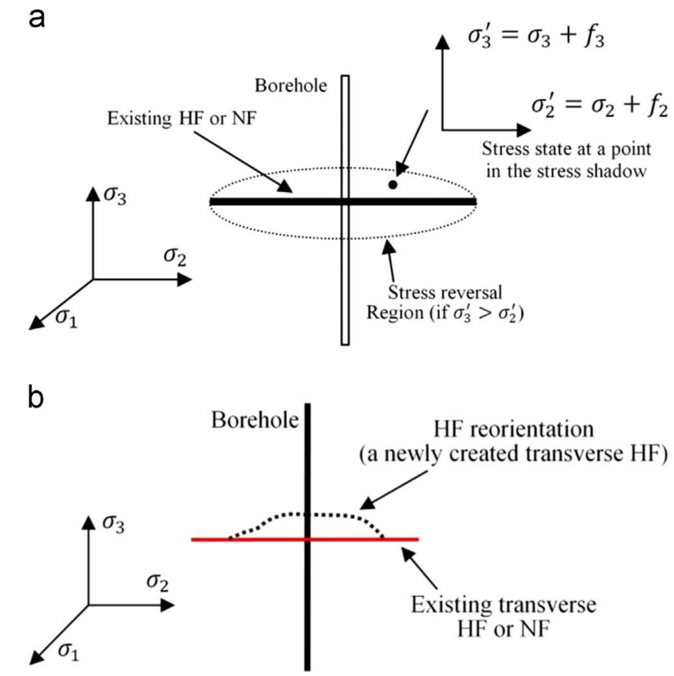

Fig. 2. Stress shadow effect and resultant HF re-orientation.[29] (a) stress shadow due to a fracture with the re-distributed stress state; (b) re-orientation of a closely located HF towards the pre-existing fracture that created the stress shadow.

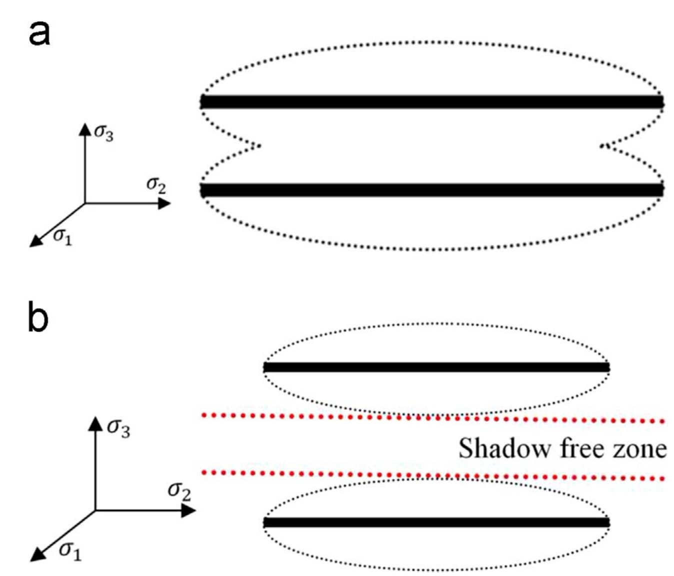

Fig. 3. Potential stress conditions due to two pre-existing fractures. (a) two closely located fractures resulting in overlapping stress shadows; (b) two fractures far apart such that their stress shadows do not intersect or overlap thereby leaving a stress shadow free zone between them.

directions respectively. The resultant stress state near fracture surfaces is the superimposition of the fracture induced stress state and the in-situ stress state as shown in Fig. 2a.

Based on linear elastic fracture mechanics, both f_2 and f_3 are compressive in the stress shadow region of the fracture with the magnitude of f_3 being much larger than that of f_2.[23] Previous studies [20–22] reveal that if the difference between f_2 and f_3 exceeds the difference between σ_2 and σ_3 in the stress shadow region, the minimum principal stress orientation in this region now becomes that of σ'_2 (the superimposed stress pointing towards the far field σ_2 orientation). If an hydraulic fracture initiates in or propagates into this stress reversal region, its propagation path will be re-orientated against its theoretically predicted direction due to the local stress change. This phenom-