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Research Paper

Effects of in-situ stresses on the fracturing of rock by blasting

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ABSTRACT

Blasting is widely applied in deep rock excavation. The effect of in-situ stresses on the fracturing of rock due to blasting was investigated. A theoretical model was used to explain the effect mechanism of in-situ stresses on crack propagation due to blasting. Four cases with different in-situ stress conditions were numerically investigated. The numerical results indicate that the crack propagation is governed by the blast load in the vicinity of the blasthole while the high in-situ stresses can influence the crack propagation in the far-field. The crack propagation trends towards the direction in which the high initial pressure is applied.

1. Introduction

With the increasing demand for natural resources, surface and subsurface mines are getting depleted and underground mines continue to progress at deeper levels. The depths of many mines around the world are more than 1000 m below the surface. For example, the mining depth of TauTona gold mine was extended to 3900 m underground with the addition of a secondary shaft in 2008 [1]. High in-situ stress is one of the main properties of deep mines. The in-situ stress is about 100 MPa at 3500 m at TauTona gold mine [2].

The drill and blast technique is the most commonly used excavation technique in mining practice. The rock fragmentation by blasting has much influence on the downstream process such as digging and hauling, crushing and grinding. During the rock blasting, the rock is originally under a pre-existing in-situ stress condition. For surface and shallow sub-surface mines, the in-situ stress is usually small and it has negligible effect on the rock fragmentation. For deep mines, the in-situ stress is close to or greater than the uniaxial compressive strength of the rock. The rock at great depth shows different properties from the rock at small depth due to high in-situ stresses. With the development of deep mining, various abnormal phenomena in deep rock have been observed, such as the large scale zonal disintegration of rock masses [3,4], the failure mode of rock from brittleness to ductility [5], the exponential increment of rock burst accidents [6] and mining-induced seismicity [7].

A lot of research has been done in the area of crack initiation and propagation due to blasting in the presence of confining stresses. Field tests conducted by Nicholls et al. [8] indicated that it is much easier to presplit in the direction of the maximum in situ compressive stress than at any angle to this direction. Blast-induced dynamic fracture tests with additional uniaxial static stress were performed on rock discs by Kutter and Fairhurst [9]. The resulting fractures clearly demonstrate the influence of the static stress field upon preferred crack direction. Some of the cracks in the test specimen, which originally started in a radial direction other than that of the maximum principal stress, eventually curved off into the direction of the applied static stress field. Simaha et al. [10] conducted a series of experiments with Plexiglass discs to study the influence of a static stress field on the fracture pattern due to blasting. The outcomes showed that the preferred fracturing is in the direction of the maximum principal stresses. Yang et al. [11] studied the behaviors of blast-induced crack in the dynamic-static stress field via caustics experiments. Their results indicated that the pre-compression stress reduces the stress concentration degree at the crack tip and hinders the crack propagation when the pre-compression stress is perpendicular to the crack propagation direction. When the pre-compression stress is parallel to the crack propagation direction, it has no influence on the crack propagation.

Numerical modelling method as a research tool has been widely used to study blast-induced damage or fracturing of rock. Finite element method (FEM) could be the most common methodology for rock blasting modelling. Yi et al. [12] investigated the blast-induced fragmentation in sublevel caving mines by using LS-DYNA code. The effect of delay time and the position of detonator on the fragmentation was discussed in this paper. Bendezu et al. [13] presented a numerical analysis based on the finite element method to simulate blast-induced hard rock fracture propagation. Three different approaches were compared in their paper to simulate a rock fragmentation process. They are the extended finite element method, the conventional finite element

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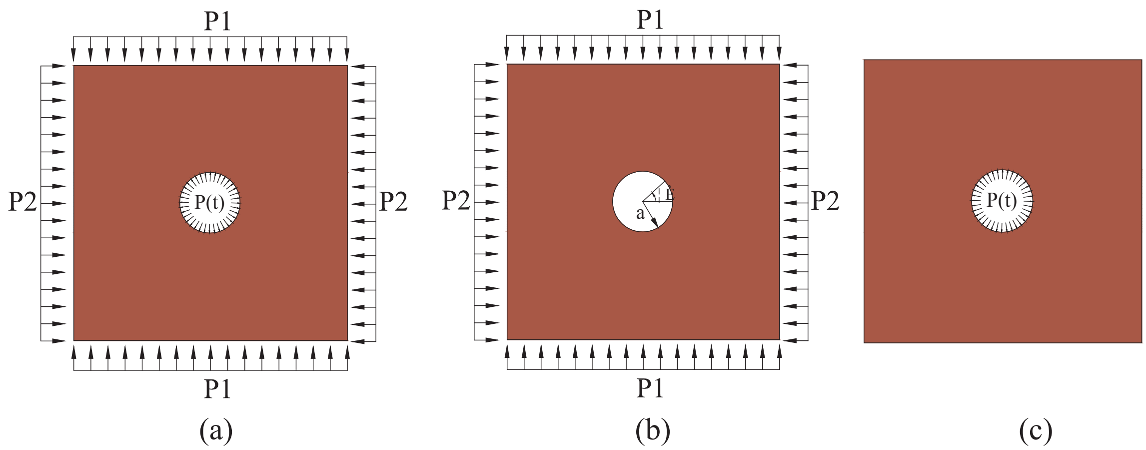

Fig. 1. Problem geometry for theoretical analysis (a) the model under the combination of dynamic and static loads (b) a single blasthole under static loads; (c) a single blasthole under blasting loads.

method and the element deletion method. It is difficult for FEM to directly model crack propagation and rock fragmentation because it is a continuum-based method. Meshless methods and hybrid mesh-meshless methods are popular recently to model rock fracturing under blasting. Fakhimi and Lanari [14] employed combining discrete element method (DEM) and smoothed-particle hydrodynamics (SPH) to model rock blasting. In their study, a bonded DEM was utilized to mimic the behavior of rock and the SPH method was used to model the detonation of explosive. Ning et al. [15] developed a discontinuous deformation analysis (DDA) framework to model blast-induced rock mass failures. An et al. [16] used a hybrid finite-discrete element method (FEM-DEM) to simulate rock fracture and resultant fragment muck-piling in various blasting scenarios. Excellent reviews on the numerical modelling of rock blasting can be found in [16–18].

Some numerical investigations on the effects of confining pressures on the blasting have been carried out. Donze et al. [19] investigated the importance of stress waves on the initiation and propagation of radial fractures during the dynamic loading phase of an explosion with discrete element methods. Their results showed that the fractures align along the main stress axis when the specimen is subjected to uniaxial compression. Ma & An [20] used a two dimensional model to study the effect of pre-compressive stress on blasting-induced rock fracture. Numerical simulation conducted by Zhu et al. [21] showed that the extent of the damage zone around the boreholes is closely related to the in-situ stress because the lateral pressure coefficient controls the stress distribution around the boreholes before the blasting load is applied. The crack propagation direction is also affected by the in-situ stress distribution. Yilmaz and Unlu [22] studied the effect of the directions and the magnitudes of major principle stresses of in-situ stress on the development of the crack zone around the borehole by using FLAC code. Xie et al. [23] investigated the damage evolution mechanisms of rock in deep tunnels induced by cut blasting. Their results indicate that the high in-situ stress has the resistance on the radially oriented pressure and the damage extension around cut holes. The coefficients of lateral pressure influence the extending direction of the tensile damage zone. Xie et al. [24] studied the effect of high in-situ stress on blast performance and optimized the blast design for cutting blast design based on the numerical results.

A lot of work on the response of rocks under the general coupled static-dynamic load has been done. Impulsive loading tests under confining pressure were performed by Sato et al. [25] to investigate the dynamic fracture properties of rocks in a triaxial stress state. Their results show that the dynamic fracture strength increases linearly with the increase of the confining pressure and is in parallel to the curve of static strength. An investigation conducted by Chen et al. [26] indicated that rock might be broken more easily under static-dynamic loading than under only the dynamic loading. Li et al. [27] argued that the appropriate coupling of static and dynamic loading can improve energy utilization efficiency in rock drilling and boring, and also improve the corresponding fragmentation of rock in the deep mining and underground cavern excavation. The investigation of Lu et al. [28] indicated that blast excavation means the transient release of in-situ stress and accumulated elastic strain energy in the rock mass. The transient release of high in-situ stress can induce vibration in the rock. Yang et al. [29] argued that the transient release of high in-situ stress due to blasting excavation is one of the factors for microseism in the deep rock mass.

The investigations mentioned above provided some good insights about the influence of initial stress on crack development due to blasting. In previous numerical investigations on the effect of initial stress of the blast-induced fragmentation, the blast load was usually represented by a pressure-time history curve [19–21]. The choices of the peak pressure, the load function and the duration of the blast load are still under debate. They cannot accurately characterize the detonation of explosive. In this paper, a model of coupling static and dynamic loads is firstly presented to improve the understanding on the mechanism of the static stress field on blast-induce fracture in the rock. Then the LS-DYNA code [30] is employed to numerically investigate the influence of in-situ stress on blast-induced damage evolution around a single borehole in the rock. In this modelling, the detonation of explosive was directly modeled with a high explosive model in LS-DYNA. The initiation and propagation of cracks under the combining blast loads and in-situ stresses is analyzed based on the damage evolution.

2. Stress distributions around blasthole under static and dynamic loads

The geometry of a single blasthole under static and dynamic loads is shown in Fig. 1(a) which shows a plate assumed to be infinite containing a circular hole with radius of a at its center. The plate is subjected to biaxial compression and the central circular hole is loaded by the explosive pressure. It can be treated as the superposition of a static loading model (Fig. 1(b)) and a dynamic loading model (Fig. 1(c)).

2.1. Stress distributions under static loads

The complete solutions for stress distributions in polar coordinates in Fig. 1(b) are [31]: