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Numerical investigation of blasting-induced damage in cylindrical rocks

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Abstract

In order to investigate rock fracture and fragmentation mechanisms under dynamic loading, a cylindrical rock model with a centralized borehole is developed through the use of AUTODYN code. According to the material properties and loading conditions, four kinds of equation of state (EOS), linear, shock, compaction and ideal gas, are applied to the four kinds of materials employed in this numerical model. A modified principal stress failure criterion is applied to determining material status, and a well-behaved explosive, PETN, and a relatively homogeneous igneous rock, diorite, are used in this rock model. A single centrally located line source of explosive is fired numerically to produce the dynamic loadings operating on the surrounding rocks. This numerical model is applied to actual blasting conditions. The rock failure mechanism under dynamic loading is first analyzed, and then the influences of the following factors on rock fracturing are discussed: (a) coupling medium, (b) confinement, (c) boundary condition, (d) initiation location in an explosive column, and (e) air ducking. The results show that all these factors have significant effects on rock fracturing under dynamic loading.

Keywords: Dynamic fracture; Blasting; Numerical model; Stress wave; Crack propagation

1. Introduction

Blasting of large masses of rock in mining and quarrying is a complex process. The efficiency of such operations depends on the knowledge of the detonation properties of the explosive and the response of the surrounding rock mass. This is because the processes of rock fracture and fragmentation around a borehole are strongly dependent on the parameters of the detonation and the dynamic response of the rock, as demonstrated in field experiments [1–3] and in bench-scale experiments [4]. The detonation properties of the explosive consist of the explosion pressure, its time history, and the total energy delivered to the rock. The response of the rock mass to such time-varying high-amplitude stresses is even more complex, as all the relevant strain-rate-dependent properties of the subject rock are not known. Under this scenario, it is essential to implement both experimental study and numerical study. The experimental study could generate an experimental database, and the numerical study could simulate the processes of rock fracture and fragmentation through the use of numerical models so as to obtain a better understanding of the dominant parameters that control blast results.

Grady and Kipp [5] applied a fracture model coupled with a material description for stress wave propagation to predict quantitatively fracture and fragmentation under explosive loading conditions. Stecher and Fourney [6] used a model that joins an energy release rate versus crack velocity fracture criterion with a two-dimensional finite difference computer program to predict the propagation of a crack that is initiated and driven by an explosive loading. Nilson et al. [7] developed a computational model to predict the propagation of gas-driven fractures emanating from a pressurized borehole, and their calculation of peak pressure, pressure-decay time, and fracture extent are in good agreement with several sets data from the propellant-driven field experiments. In order to simulate the flying distance, muckpile and damage of remaining rock mass in blasting operations, Munjiza and Owen [8] developed a discrete element model for rock blasting. In their model,

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the interaction between solid rock and detonation gas were considered in order to evaluate the pressure of detonation gas. And later, they developed a combined finite-discrete element model in transient dynamics of fracturing solids [9]. Preece and Thorne [10] used 3D finite element techniques and a damage constitutive model to study the detonation timing and fragmentation. Donze et al. [11] applied a model based on the discrete element to investigate the importance of stress waves on the initiation and propagation of radial fractures during the dynamic loading phase of an explosive. Using AUTODYN code, Ma et al. [12] simulated shock wave propagation in rock mass induced by an underground explosion. And their numerical results agree favorably well with those obtained from an independently conducted field tests. In order to verify the dynamic fracture mechanism related to blast-induced borehole breakdown, Cho and Kaneko [13] developed a numerical model to analyze the dynamic fracture process for different waveforms of borehole pressure. By using UEDC code, Chen and Zhao [14] have simulated blasting wave propagation in joint rock mass, and Gong et al. [15,16] have studied the relationship of joint spacing and joint orientation with rock fragmentation by using TBM cutters.

In rock blasting, it is generally agreed that two types of loadings, stress wave and explosion gas pressure, operate on the surrounding rock during an explosion [17–20]. A stress wave loading travels outward from the detonation of explosive column in a borehole, and it is immediately followed by a longer duration gas pressure loading [21,22]. Both loadings play a very important role in rock fracture and fragmentation. This study will focus on the stress wave loading because rock fracturing under stress wave loading is a critical step in our understanding of rock fragmentation by blasting. The cracking process under stress wave loading is considered the crucial stage as the nature of all subsequent crack extension, branching and coalescence would be largely governed by the initial crack patterns generated by the stress wave loading. These have very important bearings on control and predictions of fracture and fragmentation of rock in actual blasting.

A numerical code, AUTODYN [23,24], is applied in this study, which is an explicit finite difference code for solving a wide variety of non-linear problems in solid, fluid and gas dynamics. AUTODYN code has been successfully applied in the study of rock fracturing by Ma et al. [12] and Zhu et al. [25]. In this study, the Lagrange processor is applied, and only for the case of air-coupling, Euler processor is applied, which is ideally suited to simulating the problems of fluid and gas flow. Additional details on the interactions between subgrids, such as Lagrange–Lagrange and Lagrange–Euler coupling can be found in [23,24]. The governing equations applied in AUTODYN code are mass conservation, momentum conservation, and energy conservation.

In order to investigate the mechanism of rock dynamic fracture under stress wave loading, Zhu et al. [25] have developed a dynamic numerical model of a circular rock with a single centralized borehole through the use of AUTODYN code. Three basic fracture zones, i.e., crushed zone, severely fractured zone and incipiently cracked zone around a borehole as well as the circumferential spalling cracks have been successfully simulated in the blasting process. The fracturing mechanism under blasting loading has been analyzed, and the factors that influence rock fracturing have been discussed. This paper will continue the former study, and the model considered here is a cylindrical rock containing a single centrally located line source of explosive. According to the loading conditions and material properties, four kinds of equation of state (EOS), linear, shock, compaction and ideal gas, are applied to the four kinds of materials employed in this numerical model. A modified principal stress failure criterion is applied to determining material status, which is suitable for describing material tensile failure or shear failure. The dynamic loadings are produced from a single centrally located line source of explosive which is fired numerically. In order to minimize the various variables and the associated uncertainties of the explosive and rock, a well-behaved explosive, PETN, and a relatively homogeneous igneous rock, diorite, are employed in this simulation. The material statuses of the rock model as a function of time from the exploding source are presented and the rock fracturing mechanisms are analyzed. Finally, some factors that influence rock fracturing are investigated, and several conclusions are presented. Throughout this work, tensile stress is positive and compressive stress is negative.

2. A cylindrical rock model

In this study, a cylindrical rock containing a single centrally located line source of explosive and coupling medium are considered (see Fig. 1). The cylindrical rock measures 100 mm in diameter and 130 mm in length. The line source of explosive is represented by a single strand of detonating cord containing a core load of PETN explosive (1.1 g/m and 1.08 mm in diameter) surrounded by a thin sheath of polyethylene, with the total diameter of 2.36 mm. Coupling medium is filled in the place between the borehole

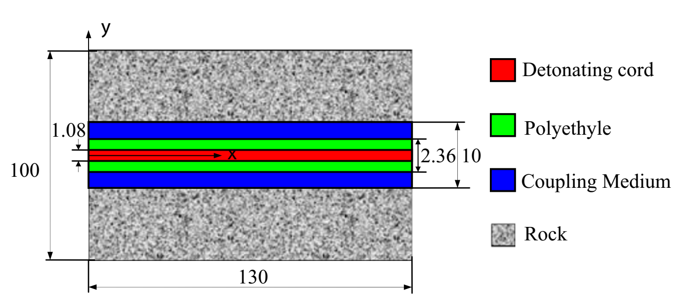

Fig. 1. Schematic of a cylindrical rock containing a centrally located detonating cord; coupling medium is filled in the place between the charge and the borehole wall; the unit is millimeter.