International Journal of Rock Mechanics & Mining Sciences 86 (2016) 55–64

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

A new geometrical-statistical algorithm for predicting two-dimensional distribution of rock fragments caused by blasting

Moein Bahadori [a], Hassan Bakhshandeh Amnieh [b,*], Asadolah Khajezadeh [c]

[a] Department of Mining Engineering, Faculty of Engineering, University of Kashan, Iran
[b] School of Mining, College of Engineering, University of Tehran, Iran
[c] Miduk Copper Mine, ShahrBabak, Kerman, Iran

ARTICLE INFO

Article history:
Received 22 September 2015
Received in revised form
19 January 2016
Accepted 1 April 2016
Available online 14 April 2016

Keywords:
Blasting
Numerical modeling techniques
Geometrical-statistical algorithm
Fragmentation
Size distribution

ABSTRACT

Four techniques, namely Voronoi, orthogonal, randomized fracture and an innovative geometric-statistical algorithm are modeled and the results are compared with the size distribution from image analysis of the field data from rock fragmentation by blasting. The results show that the proposed algorithm has higher ability in accurate prediction of real size distribution compared to image analysis. The coefficient of correlation and mean square error of prediction obtained through the algorithm were 0.9991 and 1.726, respectively. Since all these algorithms use statistical logics, 25 outputs of the models were recorded and compared. These results show that the proposed model has the greatest variance and estimates the mean size of distribution data more accurately. Also the uniformity index of proposed algorithm shows the average variance while it keeps the non-uniformity as comes from the real data. Other models show more uniform predictions. It could be concluded that the proposed model has the ability to be used in 3D modeling of rock fragmentation by blasting.

1. Introduction

Explosion is a very rapid physicochemical process that releases enormous amounts of energy in terms of light, sound, shock waves, and very high heat and pressure in a fraction of a second[1,2]. Sudden changes in the space between the molecules from a few angstroms in unburned explosives to a few millimeters in explosion products that occurs in a fraction of a second, applies shock waves to the rock mass adjacent to the blast hole[2–4]. The initial energy caused by an explosion is so large that will crush down a specific range of the immediate blast hole wall. As the distance increases and the blasting energy decreases due to severe deformations in the first zone, another set of plastic deformations appears around the blast hole outside the scope of the powdered zone; an area which is called the cracked zone[1,2]. The growth of these cracks is completed with the release of gaseous products of explosion[1,2]. The compressive waves are reflected from the free surface as tensile waves, and another group of fractures will be created in the form of spalling[5–7]. The most important function of any blast is to crush rocks into such dimensions that the largest ones do not cause any difficulties to the hauling systems, and the finer particles do not harm the processing system[1]. Singh' research shows that only 20–30% of the energy from the blast is spent on crushing the rock mass and the rest causes unwanted results such as flyrocks, ground vibrations and airblast, back-break and undesirable movement of the muck pile.

Predicting and controlling these unwanted results is so important and has significant effects on operation costs[8]. Thus, many researchers have tried to use numerical techniques[9–15] field and laboratory studies[16–25] and analytical investigations[26–28] to predict various blasting outcomes and proposed methods to optimize the results. Among these methods, although numerical modeling has its own shortcomings and limitations, it is commonly used in blasting investigations due to significant save in time and expenses and because of continuous developments in computer systems. Fragmentation behavior of materials is different under dynamic and static loads. However, statistical estimates of shape, dimensions and size distribution are very important since they help us avoid shrinking the size of elements which in turn causes increase in the number of calculations in numerical modeling and the time spent on those calculations. In a dynamic process such as an explosion, rock fragmentation is very random and controlled by the interactions among rock mass properties (in situ stress, joints and micro-cracks, material resistance and layering system), the explosive properties (velocity of detonation, explosive density, detonation pressure and resistance to water of an explosion) and the blast pattern (direction of the blast, burden and spacing, hole depth and delay times) and properly understanding this behavior

* Corresponding author.
E-mail address: hbakhshandeh@ut.ac.ir (H. Bakhshandeh Amnieh).

http://dx.doi.org/10.1016/j.ijrmms.2016.04.002
1365-1609/

is dependent on direct observation and experience[1,2,29,30].

Methods of calculation and algorithms used in numerical models to describe fragmentation mechanism of an explosion can be divided into three general groups: Pre-fractured models (DEM), continuous models which provide the possibility of plastic deformation in elements (FEM) and new hybrid models (XFEM). In the first group, using discrete element logic (DEM, DDM and DDA), the area is fractured into the desired parts before the blast loading starts. In these methods, plastic deformation and cracks are allowed to be grown only in predefined paths and fragmentation process of the whole mass is modeled. In order to model the fracture logically, the strength properties of artificial fractures are assumed to be equal to those of the rock material. Therefore, to reduce the size and increase the accuracy of calculations, the behavioral criterion of the blocks surrounded by several artificial joints is supposed to be elastic so that further damping due to plastic deformation in the blocks is prevented. Kirby et al. and Harris from Sandia National Laboratories, have provided the "SABREX" commercial code for analyzing the blasting mechanism in rock-masses, where the whole area is broken down into uniform particles before applying the dynamic explosion loading with the assumption that the pile movement starts from the free surface[31,32]. Although Harris showed that the results of numerical modeling using SABREX code have good accordance with the results of field blasting, the code has some limitations in estimating the in situ properties of the rock mass and discontinuities strength, explosive features and rock fragmentation.

To estimate the pile movement potential by different explosives and control the mixture of ore and waste, Yang and Kavetsky and Yang et al., have provided computer codes in 1989 and 1990, respectively. The codes were capable of implementing a variety of drilling patterns, setting primary boundaries between waste and ore, measuring delays between sequential rows, calculating the damping energy transferred to the blocks and introducing a coefficient to determine the explosives power. The results include different cross-sections of the final situations of the muck-pile and the grade distribution. The most important weaknesses of the model proposed by Yang and Kavetsky and the SABREX code, are assumed uniform size distribution of pre-fractured blocks in the area and lack of strength between the adjacent blocks[33,34]. To numerically model the explosion process and the muck pile movement, Preece and Knudsen from Sandia National Laboratory, provided several two-dimensional models of mock pile movement due to the expansion of gases caused by blasting. These models were called DMC (Distinct Motion Code) models whose most important feature was their capability to implement JWL equation-of-state into the blast hole. Like in previous models, the area is pre-fractured into balls with uniform size (no resistance) before dynamic loading starts[35].

Preece and Chang, added the ability of analyzing coal strength properties to DMC in order to investigate the damage to the surface layers of coal in cast blasting operations[36]. To investigate the ore grade distribution in final muck pile, Firth and Taylor have modeled the process of blasting a hole using UDEC discrete element software[37]. In this study, to model the fragmentation by the blast, the two arranged intersecting joint sets (15° and 135°) with a friction angle of 20° and stiffness of 1000 GPa were arranged with the assumption that the block was rigid. The resistances of cohesion and tension between the adjacent blocks, the effects of gases produced by blasting, are neglected and the fragmentation is assumed to be completely uniform. Mortazavi and Katsabanis have performed some numerical modeling using the DDA method to investigate the effect of burden size on blasting results[38]. In these simulations, the area is pre-fractured by sets of artificial discontinuities into completely uniform fragments and the influence of the dip of these discontinuities on pile movement is investigated. Wang and Konietzky have modeled the explosion loading process and crack propagation around the blast hole (pre-fracture models using orthogonal joint sets and Voronoi tessellation algorithms) in LS-DYNA and UDEC software, respectively. The results showed that implementing tessellation algorithm in estimation of the crack pattern around blast hole has better consistency[39].

In addition, since 2001, an international project has been carried out by Queensland University in Australia, Cambridge and Leeds universities in the United Kingdom and the ITASCA group of consultants to provide a detailed numerical modeling method with the ability of simulating the blast loading, fracturing and fragmentation processes in the rock mass and the eventual pile movement. This project which is called "Hybrid Stress Blasting Model (HSBM)" uses hybrid computations of continuous and discontinuous calculation logics in evaluating the results of rock fragmentation by blasting. The computational logic used in HSBM, is an adaptation of DMC calculation method. In HSBM, the blasting process is modeled in three separate ranges of the explosive material column, the powdered zone (2.5 times larger than the radius of the hole) and the cracks caused by the blasting, using three different computational logics. PFC logic is used to model the fractured zone and thus the rock mass is broken down into pieces with a specified uniform size before blasting[12]. These pieces are connected by the Kelvin-Voigt equation (parallel spring and damper) and tensile strength. In this model, the estimated fragmentation intensity, depends on the network size and since all the fractured area (outside the powdered region) is modeled using this network, reducing network size, will considerably increase the number calculations and the time spent on them[12].

Ning et al. used DDA to estimate the muck pile geometry after the blast. In this study, the blasted area had been fragmented into uniform triangles before the dynamic loading started[10]. Dare-Bryan et al. have devised a hybrid computer code in order to control and optimize the size of fragmented blocks and provide for an appropriate uniform size, improve the quality of controlled blasting and pre-fracturing, optimize the surface pit design for maximum haulage system efficiency and prevent the crushed materials from collapsing on the downstream stairs in Billiton uranium mine. In this model, the fracturing process occurs prior to blasting, and the representative fragmentation blocks are connected only by the tensile strength[40,41]. In the second category of modeling, plastic deformation zones and the cracks extending from around the blast hole are described using plastic deformation continuity in a certain direction. This means that in a continuous logic, the plastic deformation of consecutive elements, is assumed to be an equivalent of the crack propagation path[42]. Limitations of this method include lack of true simulation of failure mechanism due to the impossibility of creating a new free surface, reflection and distortion of waves on the surface and increase in calculation error when the fracture line (along the deformed elements) intersects the outer boundary in models with small dimensions. An escape from the second error could be selecting a primary model with large dimensions (farther boundaries), which will in turn increase the number of calculations and the time spent on them[42]. Zhou et al. used AUTODYN finite element software to investigate the damage caused by blast loading in cylindrical samples of rock. These researchers regarded the development of plastic deformation in specified elements as a symbol of crack growth[43]. Ma and An used LS-DYNA finite element software to investigate the effect of duration pulse detonation on the expansion of plastic deformation zones around the blast hole. In this study, changes in the distribution of fractures around the blast hole as a result of variation in the duration of a pressure-time pulse (with the same maximum of detonation pressure) was investigated. The results showed that by increasing the duration of dynamic loading, the radius of the area around the blast hole, changes from the mere crushed state to several unique radial