Numerical modeling of rock blasting: Validation tests for *Blo-Up 2.5*

J.K. Furtney & P.A. Cundall
Itasca Consulting Group, Inc., Minneapolis, MN, USA

I. Onederra
University of Queensland, WH Bryan Mining and Geology Research Centre, Australia

E. Sellers
AEL Mining Services, Johannesburg, South Africa

ABSTRACT: As part of the Hybrid Stress Blast Model (HSBM) project, Itasca has developed software to model the rock blasting process. The code, called *Blo-Up 2.5*, uses a unique combination of three-dimensional continuous and discontinuous numerical methods to represent the key processes occurring in non-ideal detonation, rock fracturing and muck pile formation. Itasca's continuum rock mechanics code *FLAC* is used to represent the shear failure characteristic of the near field. *FLAC* is coupled to a custom discrete element (DEM) code which models the wave propagation and initial fragmentation through to muck pile formation. Recently, significant work has been undertaken by the project sponsors and researchers to design and evaluate a series of validation cases for this new technology. The HSBM project has had an ongoing collaboration with the National Institute for Occupational Safety and Health (NIOSH) involving blasts experiments on concrete cubes. HSBM sponsor and research partner AEL Mining Services performed a series of instrumented test blasts on concrete cubes. This paper compares the *Blo-Up 2.5* numerical model to these validation experiments.

1 INTRODUCTION

Motivated by a desire for a better understanding of the blasting process, a group of mining companies have supported the collaborative HSBM (Hybrid Stress Blast Model) research project since 2001. The objective of this project has been to develop a model of the complete blasting process including non-ideal detonation. The researchers have included the University of Queensland, the University of Cambridge, Imperial College, Leeds University and Itasca Consulting Group. Itasca has contributed the rock breakage engine *Blo-Up 2.5*. *Blo-Up* originally stood for Blast Layout Optimization Using PFC^{3D} as the first version was a wrapper around PFC^{3D} 3.1 (Itasca 2008b) which incorporated specialized detonation logic and a reaction product flow model (Ruest et al. 2006). As part of the HSBM 2 project Itasca developed *Blo-Up 2.5*, a complete rewrite of the original code based on a custom continuous/discrete numerical technique.

The primary goal of this project is to develop a code to predict fracturing and fragmentation for a given set of blast parameters and rock properties. Secondary goals include predictions of throw, grade movement and muck-pile shape. The model is expected to produce the general trends in fracturing and fragmentation observed in the field but is not expected to reproduce every detail of a real-world blast. Further, it is expected that the code will predict realistic trends in fragmentation as inputs are varied, allowing it to be used as a blast scenario research tool.

This work gives an overview of the HSBM project software and presents some new validation results. The paper consists of three parts:
1 a brief description of the algorithms used in *Blo-Up 2.5*,
2 details of the HSBM-NIOSH validation collaboration, and
3 details of the AEL managed Bronkhorstspruit concrete cube blasting validation campaign.

2 MODEL FORMULATION

A brief summary of how *Blo-Up 2.5* is implemented is presented here; a more complete description can be found in Furtney et al. (2009).

Characterization of the explosive in terms of density, energy release, reaction extent, product equation of state (EoS) and velocity of detonation (VoD) is required as the first step of the modeling process. A non-ideal detonation code *Vixen2009*, a component of the HSBM software suite, determines these parameters and transfers them as inputs to *Blo-Up 2.5*. The detonation aspects of the HSBM project are described in more detail in Braithwaite & Sharpe (2009).

The explosive is represented as special constitutive behavior in the central zones of an axisymmetric continuum representation based on *FLAC*. A programmed burn (Kapila et al. 2006) algorithm is used to simulate the detonation process, and the expansion and axial flow of the detonation products. Energy is released into the zones representing explosive based on a pre-determined velocity of detonation. Beyond the central explosive zones a Mohr-Coulomb material represents the near-field rock. The crushing and energy loss in this region is easier to describe as a continuum constitutive law.

The *FLAC* zones representing the explosive and near field rock are coupled to a lattice type discrete element method, which is a simplification of the standard DEM calculation. The lattice method applies forces to point masses, which have only translational degrees of freedom, and the connecting springs have a tensile breaking strength. This simplification results in an increase in calculation speed by a factor of ten and a decrease in memory storage requirements by a factor of seven. The radial fracturing occurring away from the borehole is primarily tensile-mode failure, which still is represented well with the lattice-model simplifications.

The model geometry is built up of point masses distributed in a non-repeating pattern with a user specified average separation between nodes. Figure 1 shows a schematic of the lattice. Lattice nodes that overlap *FLAC* zones are velocity-controlled by the movement in the *FLAC* zones. The lattice nodes then contribute forces back to the *FLAC* zones. This mechanism provides full coupling between the lattice region and the near-field representation.

The mechanical calculation is fully coupled to a simplified gas flow model representing the high pressure reaction product gas. The expanding gas applies a force to the fragments contributing the throw. Contact detection and temporary contact springs are used to model the muck pile formation.
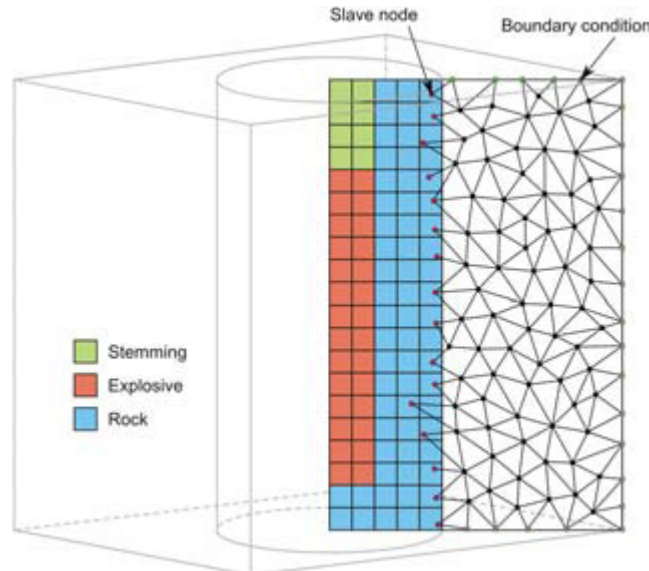

Figure 1. Schematic representation of coupled lattice *FLAC* computational domain.

3 NIOSH COLLABORATION

The HSBM researchers have been actively collaborating with a blasting group at the Spokane Research Laboratory (SRL) of the U.S. National Institute of Occupational Safety and Health (NIOSH). Information from controlled blasting experiments in large concrete blocks has been made available to the HSBM group for model evaluation and validation purposes. The goals of the modeling are to understand the influence of the free model parameters and to establish a calibration procedure. Two experiments were conducted in which concrete cubes of two different sizes and burdens were blasted with a cartridged emulsion product. The first experiment was used to calibrate the model and a forward prediction of the second experiment was made before it was conducted.

In both experiments, the blastholes were 1.8 meters long, 38 mm in diameters and nearly horizontal. In the first experiment, the concrete block was 3.05 m × 3.05 m × 1.52 m and the burden was 46 cm. In the second experiment the block was 3.7 m × 2.4 m × 1.8 m and the burden was 15.7 cm. A more detailed description of the experiments and the data collection methods is given by Iverson et al. (2009).

3.1 *Experiment one*

The geometry and experimental set up of the first concrete block experiment is shown in Figure 2. Laboratory experiments on the concrete used in the experiments yielded the following properties: Young's modulus (E) 18.6 GPa, Poisson's ratio (ν) 0.25, density (ρ) 2009 km/m^3, static tensile strength (T) 4.1 MPa, unconfined compressive strength (UCS) 21 MPa, and friction angle (ϕ) 25 degrees. Of these measured parameters E, ν, ρ, UCS and ϕ can be input directly into *Blo-Up 2.5* as rock properties. The tensile strength, the characterization of tensile strength as a function of strain rate and the damping coefficient are free variables for calibration. In addition to the parameters listed above the following inputs were found to give the best match to the fracturing observed in the experiment: damping coefficient (α) 0.8 and tensile strength parameters: T = 4.1 MPa, M = 10 and b = -3. The parameter M is the multiplier in tensile strength experienced at the highest strain rates and b describes how fast this enhanced tensile strength returns to the static strength as the strain rate decreases. Note that in the present case the laboratory measured tensile strength give a good fit to the observed results. The process of calibration is discussed more in the next section.

The geometry of the *Blo-Up 2.5* model of experiment one is shown in Figure 3. The borehole is represented at the true diameter of 38 mm and is charged to a length of 120 cm from the bottom. DYNO AP emulsion explosive was used and ideal-detonation conditions were assumed. A model resolution (average point mass spacing) of 38 mm was used. A quiet boundary condition, with an impedance ratio of unity, is applied to the lower surface and the other faces are all free surfaces.
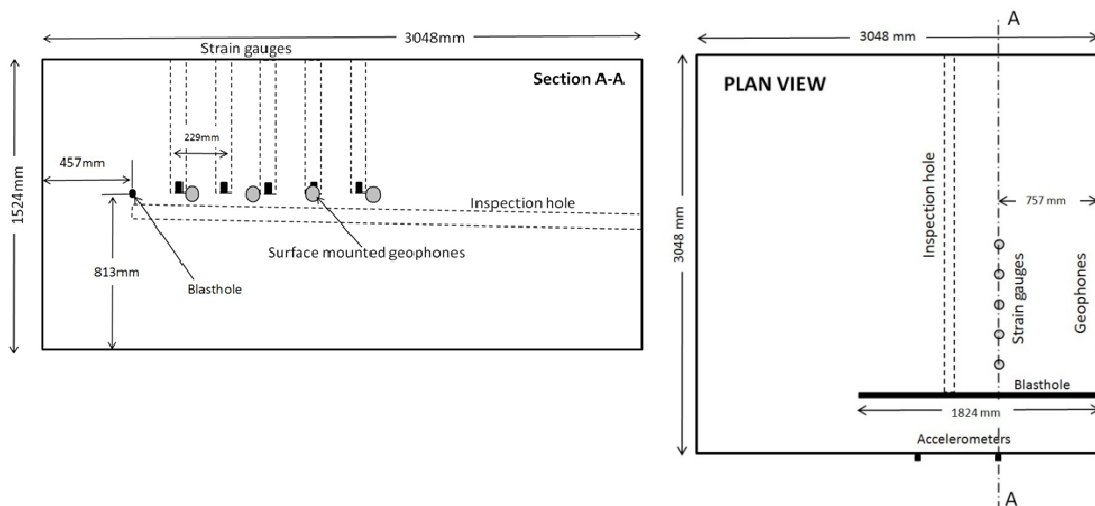

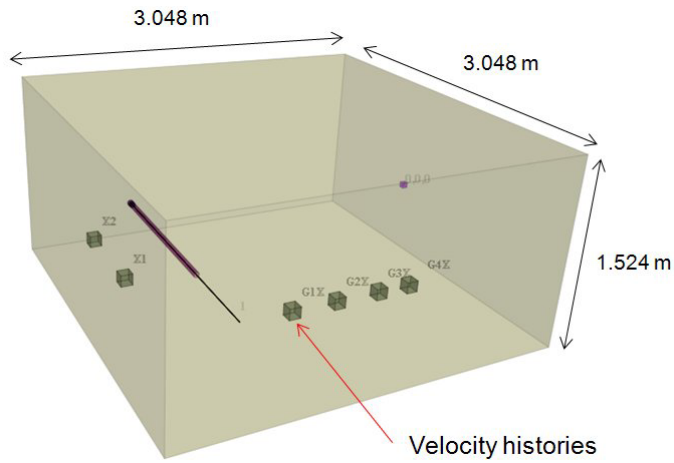Figure 2. Geometry of experiment one.

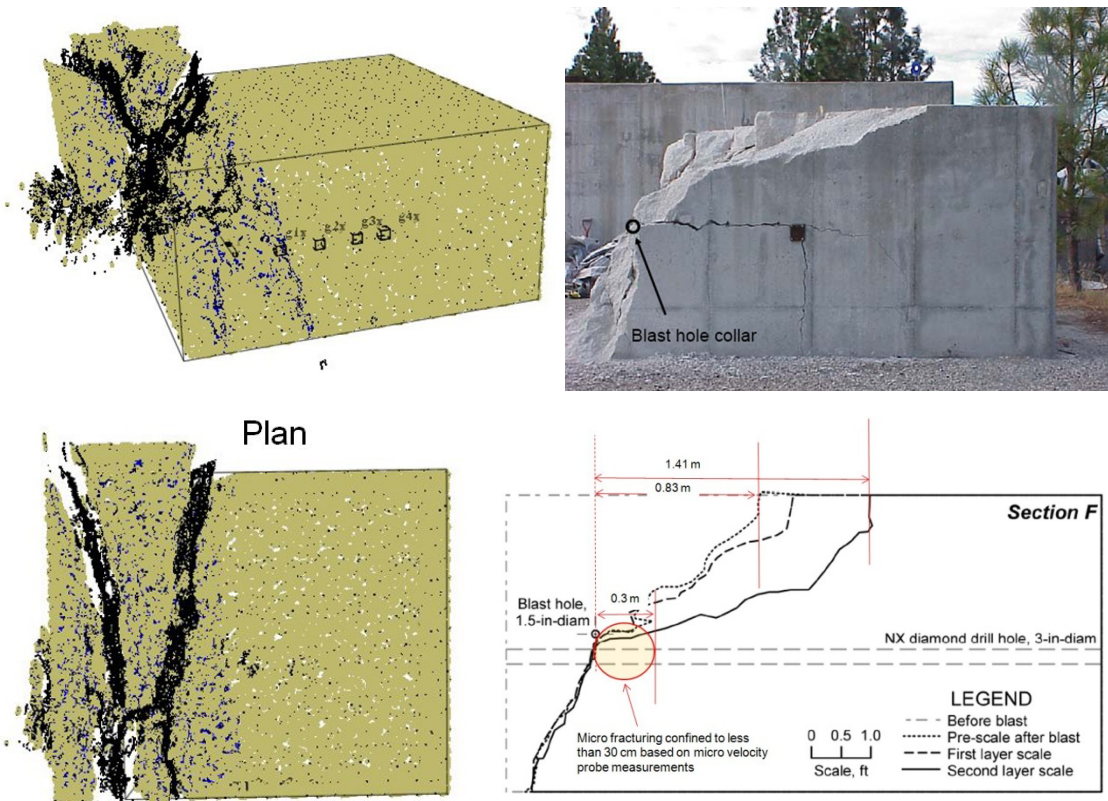Figure 3. *Blo-Up 2.5* model of experiment one.

Figure 4. *Blo-Up 2.5* model predictions are shown on the left along with measurements from the experiment.

For these model inputs, the resulting breakage and fracture patterns are shown in Figure 4 along with field measurements from experiment one. The fracturing and damage extent in the model compare reasonably well with the experimental measurements. The following conclusions were drawn from the modeling of experiment one:

1 A realistic fracturing network, fragment formation and extent of damage were observed with *Blo-Up 2.5*. Overall results compared well with post blast measurements.

2 No spalling at corners is observed in the numerical simulations, which agrees with experimental results. This indicated the requirement for a relatively high damping coefficient ($\alpha = 0.8$).

3 Face velocities of ~ 10 m/s observed in the model were considered realistic.

4 P-wave arrival times were reasonably matched between modeled and measured values.

5 Vector sum peak particle velocity attenuation was captured by the model. However peak amplitudes were approximately half of measured values. This could be attributed to the relatively high damping coefficient.

3.2 *Experiment two*

To test the ability of the model to predict the correct trends in fracturing as blast parameters are changed a forward predictions was made for the different geometry and burden in the second experiment. The second experiment was conducted in a concrete cube of smaller size, with a smaller burden and with a different concrete formulation resulting in different material properties.

Laboratory experiments of the concrete used in experiment two yielded the following results: Young's modulus (E) 20.0 GPa, Poisson's ratio (ν) 0.25, density (ρ) 2000 km/m^3, static tensile strength (T) 5.0 MPa, unconfined compressive strength (UCS) 35MPa, and friction angle (ϕ) 25 degrees. In addition, the following properties were given as inputs to *Blo-Up 2.5*: damping coefficient (α) 0.8 and tensile strength parameters: T = 5 MPa, M = 10 and b = -3. The same explosive inputs and model resolution used in experiment one were used here. Boundary conditions were the same except three separate cases were run in which the impedance ratio of the lower quiet boundary was set to 0.1, 0.5 and 1.0. This ratio controls how much energy is reflected back into the model at boundaries with acoustic impedance contrast.

Modeling results are given in Figure 5. The resulting post blast fracture (damage) maps from the experiments are shown at the bottom right of Figure 5. The following conclusions were drawn from this validation experiment:

1 Breakout radial fractures bounded by the top and bottom boundaries of the model were adequately predicted by the model.

2 The maximum extent of damage was predicted to extend to approximately 1.2 m from the centre of the blasthole in the top boundary and approximately 0.8 m in the bottom boundary. This is equivalent to the actual damage measured and recorded in the post blast fracture maps shown above.

3 Breakout angles and the main fractures were shown to be a function of the front, top and bottom boundary conditions. In particular, this type of experiment is sensitive to the material the cube is resting on; this relationship is explored more in the next section.

4 These experiments were not designed specifically as validation tests for *Blo-Up 2.5* but they have provided a good opportunity for model verification and validation.

4 SA CUBES

Building on the experience gained from modeling of the NIOSH blast study a new blast experiment was designed with the specific purpose of validating *Blo-Up 2.5*. Four identical concrete cubes, three meters on a side, were cast on a compacted soil berm in a disused quarry in Bronkhorstspruit, South Africa. Four identical experiments were conducted to allow an assessment of the variability in results. A detailed description of the test design, results and preliminary modeling of the experiment are given by Sellers et al. (2009).

A vertical borehole 1.3 meters in length with a diameter of 33 mm was precast into the cubes with 800 mm of burden. The boreholes were charged from the bottom to a height of 600 mm with 606g of explosive of density 1.18 g/cm^3. 700 mm of tightly packed sand was used as stemming. This resulted in an overall powder factor of 0.02 kg/m^3. This factor is lower than required for secondary breaking so the fragmentation is expected to be controlled by the interaction of the explosive with the burden regions and not due to splitting of the cube.
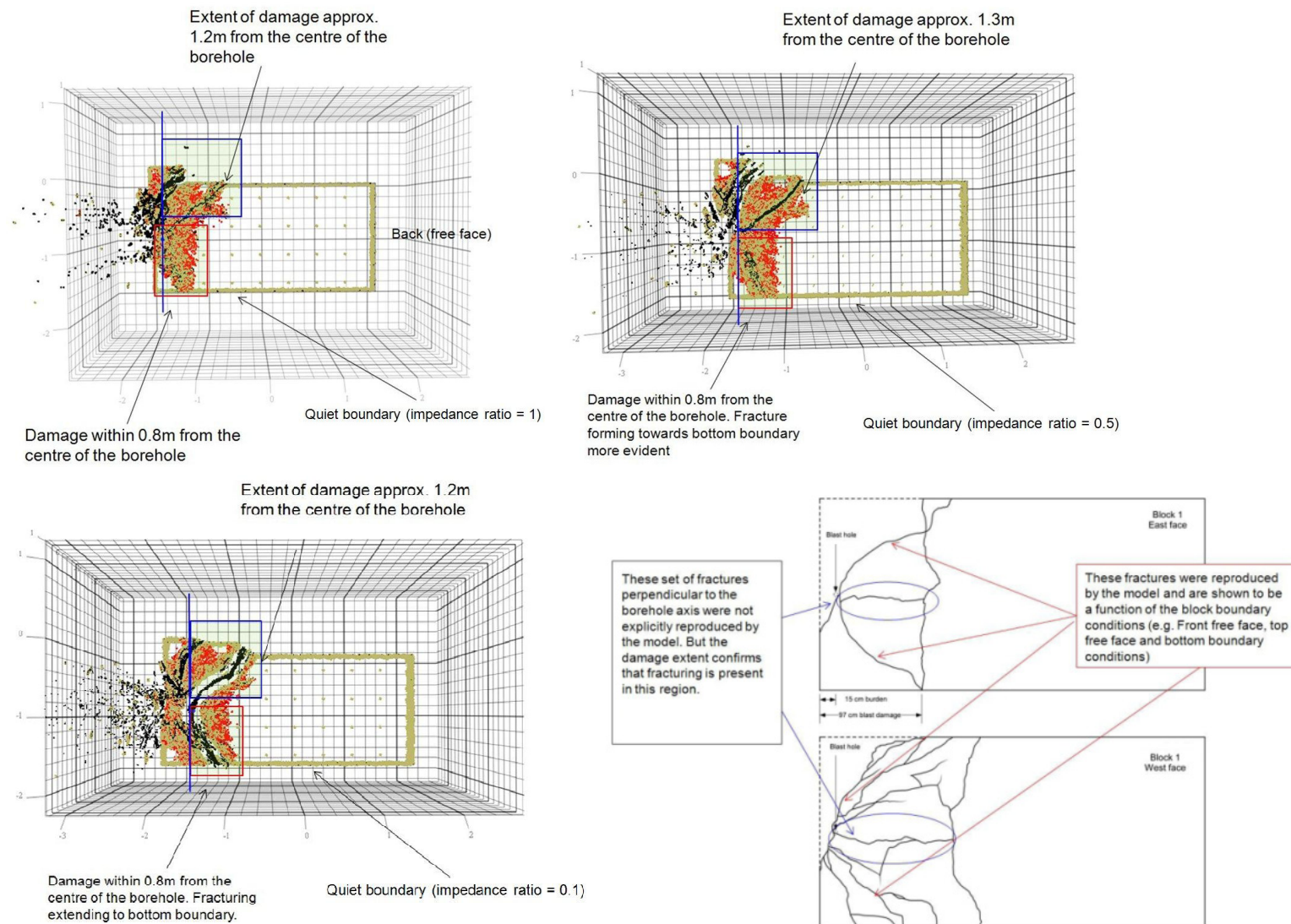
Figure 5. Model results from stage 2 experiments shown along with fracture patterns from experimental data.

Figure 6 shows block 3 during the heave phase and at the conclusion of the test. Two cubes experienced significant heave and fragmentation whereas the other two broke into large segments that were only displaced slightly.

The preliminary modeling given in Sellers et al. (2009) has been revised and updated for presentation here. Numerical experiments with *Blo-Up 2.5* have shown that cube tests of this type are sensitive to the boundary conditions at the base of the cube. To remove the influence of this boundary condition on the model results, the quarry floor is represented explicitly below and around the cube. A weak joint plane of varying size separates the cube from the quarry floor and a quiet boundary condition is applied to the edges of the quarry rock. Figure 7a shows a cross section through the *Blo-Up 2.5* model of the experiment including the quarry floor and the joint plane.

Laboratory experiments on the concrete gave the following properties: Young's modulus 23 GPa , Poisson's ratio 0.2, density 2,500 kg/m^3, UCS 45 MPa and a range in tensile strengths from 2.9 to 6.5 MPa. The following additional inputs to *Blo-Up 2.5* were found to give the best match to the experimental observations: damping coefficient (α) 0.8 and tensile strength parameters: T = 1 MPa, M = 10 and b = -3. Figures 7a, 8a, & 8b show the fragmentation resulting from cases with different conditions on the cube quarry floor interface. Figure 7b shows the case where the cube quarry floor interface is fully fixed, Figure 8a shows the case where the interface is fully separable and Figure 8b shows a partially separable lower surface. The damping coefficient (α) is 0.3 in the case shown in Figure 7b and is 0.8 in the cases shown in Figures 8a & 8b. Figure 9a shows the experimental geophone data along with the model predictions. Figure 9b shows the modeled and observed PPVs. The model geophone trace is similar in shape to the data. The peak particle velocity as a function of distance is underestimated as in the NIOSH experiment models.

In summary, after a calibration process the code is able to reproduce a realistic fracture pattern and give reasonable agreement with the experimental geophone data. As in the previous case, the model outcomes are sensitive to the lower surface boundary conditions.

Figure 6. Video capture of cube 3 showing a) fragmentation during blast and b) final configuration.
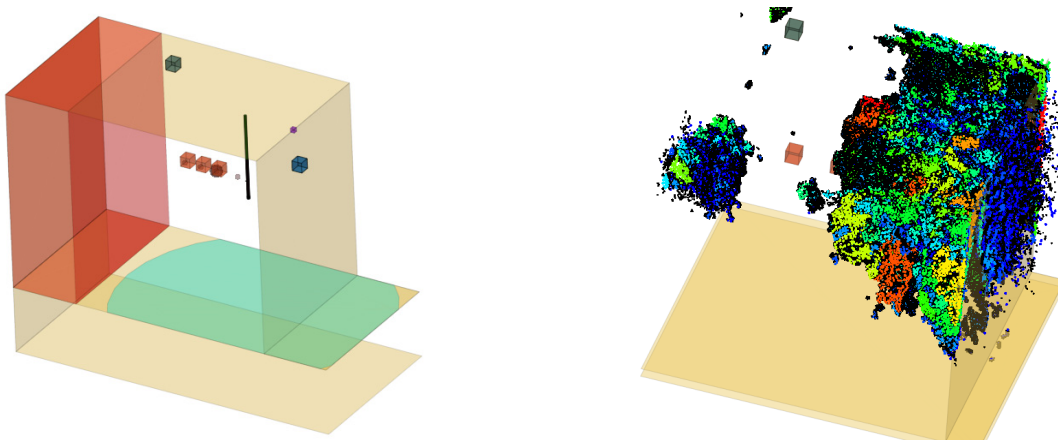

Figure 7. a) Section through the cube cut out of an open cut bench and b) predicted fragmentation for the model without any lower joint plane (damping 0.3).
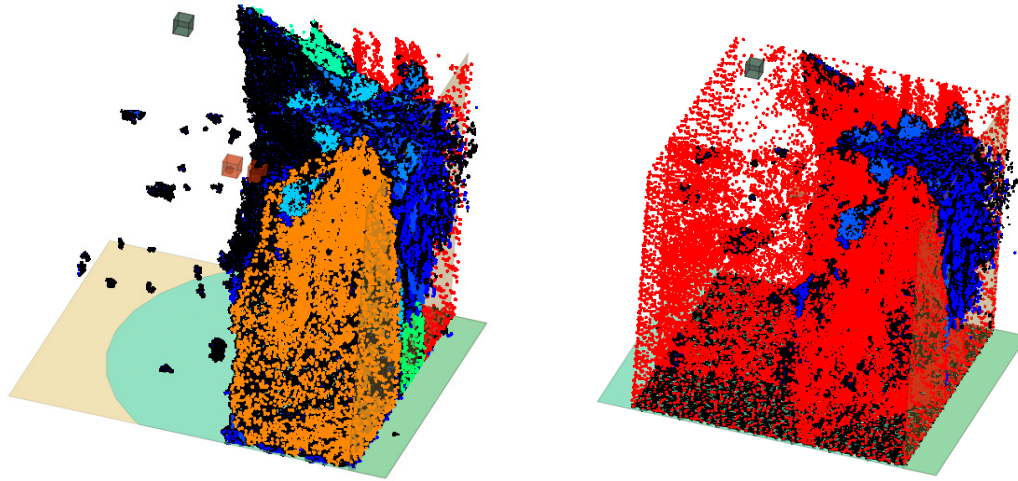
Figure 8. Fragmentation after 100 ms with a) completely separable lower surface and b) with partially separable lower surface (damping 0.8).
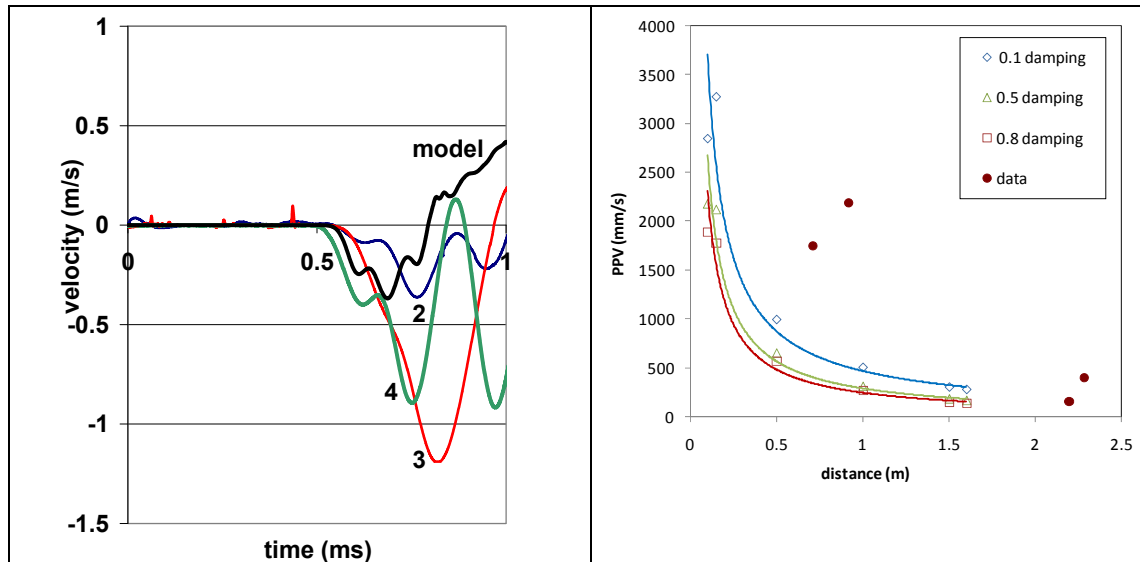

Figure 9. a) Geophone traces in x-direction measured at the back top corner for the last 3 cubes. The lines labeled 1 through 4 are the experimental results and the black line is the model prediction. b) Modeled and observed PPV with distance.

4.1 *Model calibration*

Currently, the tensile strength is the primary free variable for calibration to known fragmentation. Essentially, the mode one fracture toughness is being calibrated; this fracture toughness is made independent of model resolution through the use of a scaling factor. Additionally, the two parameter power-law model which parameterizes the tensile strength as a function of strain rate is a free variable for calibration. Other free variables include a damping coefficient and a diffusion coefficient for the gas flow model. Given the number of free parameters and the non-linearity of the model, any given combination of inputs is non-unique. There may be more that one combination of inputs which give the same outputs. In the NIOSH study the laboratory measured tensile strength was found to give good agreement with the experimental observations but in the Bronkhorstspruit cube models a significantly reduced tensile strength was required to match the experimental observations. Understanding the sensitivity of each input, reducing the model non-uniqueness and establishing a convention for calibration are ongoing challenges for the next phase of the HSBM project.

8

5 CONCLUSIONS

The numerical model *Blo-Up* 2.5 gives reasonable agreement with physical experiments (in terms of fracture patterns, fragmentation and particle velocity trends) both at the small scale (10 cm: see Onederra et al. 2009) and the intermediate scale of meters, as reported here. It is important to note that considerable variation is reported in the results from ostensibly identical physical experiments, so the expectation of close agreement between a numerical simulation and a single experimental result is unreasonable. For a system involving complex, highly dynamic and nonlinear physics, we should be satisfied if there is general similarity in fracturing and particle motion. The next phase of validation work is to compare the results of *Blo-Up 2.5* with field results at the scale of tens of meters and multiple blastholes. Additionally, the throw velocity and muck pile predictions of the code will be assessed.

REFERENCES

Braithwaite, M. & Sharpe, G. 2009. Simulation of real detonations as an energy source term for the Hybrid Stress Blasting Model. In J.A. Sanchidrian (ed.), *Proc. 9th Int. Symp. On Rock Fragmentation (Fragblast 9), Grenada, Spain, 13-17 September*.

Furtney, J.K, Cundall, P.A & Chitombo, G.D. 2009. Developments in numerical modeling of blast induced rock fragmentation: Updates from the HSBM project. In J.A. Sanchidrian (ed.), *Proc. 9th Int. Symp. On Rock Fragmentation (Fragblast 9), Grenada, Spain, 13-17 September*, 335-342.

Itasca Consulting Group, Inc. 2008a. *FLAC – Fast Lagrangian Analysis of Continua, Ver. 6.0 User's Manual*. Minneapolis: Itasca.

Itasca Consulting Group, Inc. 2008b. *PFC3D – Particle Flow Code in Three Dimensions, Ver. 4.0 User's Manual*. Minneapolis: Itasca.

Iverson, S.R., Hustrulid W.A., Johnson J.C., Tesarik, D. & Akbarzadeh, Y. 2009. The extent of blast damage from a fully coupled explosive charge. In J.A. Sanchidrian (ed.), *Proc. 9th Int. Symp. On Rock Fragmentation (Fragblast 9), Grenada, Spain, 13-17 September*, 459-468.

Kapila, A.K., Bdzil, J.B. & Stewart, B.S. 2006. On the structure and accuracy of Programmed Burn. *Combust. Theory & Modell.* 10: 289-321.

Kristiansen, J., Kure, K., Vestre, J. & Bergqvist, I. 1990. An investigation of heave and fragmentation related to explosive properties. In *Proceedings of the Third International Symposium on Rock Fragmentation by Blasting, Brisbane, Australia, August, Parkville*, Vic: Australasian Institute of Mining and Metallurgy, pp. 1-8.

Onederra, I., Cundall, P., Furtney J., and Chitombo, G. 2009. Towards a complete validation of the lattice scheme in the Hybrid Stress Blasting Model (HSBM). In J.A. Sanchidrian (ed.), *Proc. 9th Int. Symp. On Rock Fragmentation (Fragblast 9), Grenada, Spain, 13-17 September*, 343-351.

Reichholf, G. 2003. *Experimental investigation into the characteristics of particle size distributions of blasted material*. PhD Thesis. Montan University Leoben, Austria.

Ruest, M., Cundall, P., Guest, A. & Chitombo, G. 2006. Developments Using the Particle Flow Code to Simulate Rock Fragmentation by Condensed Phase Explosives. In *Proc. 8th Int. Symp. on Rock Fragmentation by Blasting (Fragblast 8), Santiago, Chile, May 2006*, pp. 140-151. Santiago: Editec.

Sellers, E., Kotze, M., Dipenaar, L., & Ruest, M. 2009. Large scale concrete cube blasts for the HSBM model. In J.A. Sanchidrian (ed.), *Proc. 9th Int. Symp. On Rock Fragmentation (Fragblast 9), Grenada, Spain, 13-17 September,* 389-398.