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Modelling of Geostructure Fracture and Fragment Muck-piling using Hybrid Finite-Discrete Element Method

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ABSTRACT

An integrated development environment is developed using Visual C++ and OpenGL for an open-source hybrid finite-discrete element method to simplify model setup, debug errors and visualize results in real-time. 2D particle flow through a draw point, 3D rock fall along a staged slope, and rock fragmentation as well as resultant fragment muck-piling are modelled using the hybrid finite-discrete element method demonstrating the capability of the integrated development environment.

Keywords: hybrid FEM/DEM, numerical modelling, rock fracture, fragment muck-piling

1 INTRODUCTION

The rapid development of modern society has resulted in the need for increased geostructures. Unfortunately, fracture, failure and collapse of geostructures occur from time to time, which cause not only economic loss but also fatalities and other notable socio-economic impacts. Thus, on one hand, to prevent the geostructures from damage, fracture, failure and collapse, it is imperative to study fracture and fragmentation of geomaterials. On the other hand, it is essential to break geostructures in a number of engineering applications, e.g. extracting valuable natural resources in the mining and energy exploitation sectors. Geomaterials are generally assumed to be continuous for the modelling of their behaviour. Continuum, mesh-based methods have been applied successfully to many problems in engineering, and a continuum approximation may be adequate when sufficiently large length scales are considered - even if the geology includes fractures and faults. However, the validity of this idealisation is limited to only sufficiently large volumes compared to the scale of the problem and individual rock discontinuity is not necessarily to be taken into account. When the structure of interest have sizes comparable with the block size, or when the structures experience loads that cause no measurable damage to individual blocks, but deformation along material discontinuities still leads to structure failure, a purely continuum, mesh-based treatment is usually inappropriate. To address this limitation, new numerical approaches have been developed over the recent decades, which include the discrete element methods (e.g. PFC, Cundall and Strack, 1979), discontinua deformation analysis (e.g. DDA, Shi and Goodman, 1988) and combined finite-discrete element method (e.g. FLAC/PFC coupling: Cai et al., 2007; LDEC: Morris et al., 2009; ELFEN: Rockfield, 2006; Y2D: Munjiza, 2004; Y3D: Xiang et al., 2009). Beyond the capabilities of the original DEM and DDA, the study of geomaterials fracture and fragment muck-piling requires a hybrid continuum-discontinuum treatment for a complete solution. However, most of hybrid continuous – discontinuous model available at this moment is similar to the FLAC and PFC coupling. The coupling may be suitable for other applications but impose important limitation in modelling geomaterials fracture and fragment muck-piling. In this paper, an integrated development environment (IDE) will firstly be developed using Visual C++ and OpenGL for the open-source hybrid finite-discrete element method, originally developed by Munjiza (2004) and Xiang et al. (2009) in its 2D and 3D versions, respectively. The hybrid finite-discrete element method will then be used to model geomaterials fracture and/or fragment muck-piling in particle flow through a draw point, rock fall along a staged slope, and rock fracture and fragment muck-piling by rock blast.

2 INTEGRATED DEVELOPMENT ENVIRONMENT FOR OPEN-SOURCE HYBRID FINITE-DISCRETE ELEMENT METHOD

The open-source hybrid finite-discrete element method, i.e. the Y2D and Y3D codes originally developed by Munjiza (2004) and Xiang et al. (2009), respectively, are robust and efficient for modelling material continuum / discontinuum behaviour. In the hybrid finite-discrete element method, one system is considered to consist of a single discrete body or a number of interactive discrete bodies. Each individual discrete body is of a general shape and size, and is modelled by a single discrete element. Each discrete element is then discretised into finite elements to analyse deformability, fracture and fragmentation, thus imposing no additional database requirements on handling the geometry of individual discrete elements. In contrast, the discrete element in the discrete element method must be of regular shape such as disc or ellipse in 2D and sphere or ellipsoid in 3D and must be rigid, i.e. un-deformable and non-fractureable. If deform and fracture have to be modelled using the discrete element method, soft contact must be used and the particles must be bonded together. The key components of the open-source finite-discrete element method include contact detection and interaction between individual bodies, deformability and transition from continuum to discontinuum through fracture, and central difference time integration scheme.

Contact detection algorithm is intended to detect couples of discrete elements close to each other and eliminate couples far from each other and impossible in contact. Several contact detection algorithms including direct checking, binary tree based search, no binary search, etc (Munjiza, 2004) are available so that optimal contact detection algorithm can be chosen depending on different types of problems such as dense or loose packing. Once couples of discrete elements in contact have been detected, contact interaction algorithm is employed to evaluate contact forces between discrete elements in contact on the basis of finite element discretisations of discrete elements and the potential contact force concept. The contact force is calculated using penalty function method based on penetration. To limit penetration, a penalty term is introduced being proportional to the modulus of elasticity. According to Munjiza (2004), errors in the displacements can be easily controlled through setting penalty term as a function of elasticity and can be reduced by reducing the size of finite element.

Fracture and fragmentation results in the transition of geomaterials from continua to discontinua. Thus, the main tasks of dealing with the transition are to predict crack initiation and propagation, model material degradation and fragmentation, perform necessary remeshing, transfer variables from the old to new meshes and replace the released internal forces with equivalent contact forces. Several approaches are available to model geomaterial fracture and fragmentation, which includes global approaches based on fracture mechanics (Rockfield, 2006), local approaches based on damage mechanics (Liu et al., 2004), discrete crack models (Munjiza, 2004), and smeared crack models (Morris et al., 2009). The discrete crack model is implemented by Munjiza (2004) in the open-source hybrid finite-discrete element method using bonding stress. Fracture and fragmentation are assumed to coincide with the element edges and separation of these edges induces a bonding stress, which is a function of the size of separation.

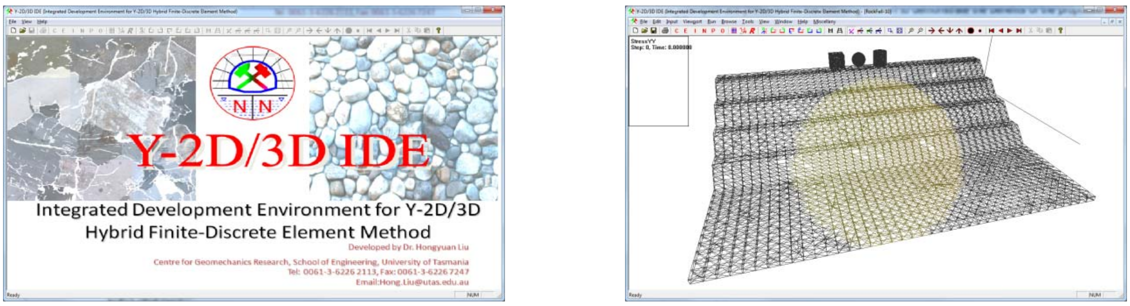

Figure 1. Integrated development environment for the open-source hybrid finite-discrete element method (Y-2D/3D IDE)

Hybrid finite-discrete element method may have to use thousands or even millions of finite element meshes in an analysis. Moreover it models deformability, rigid rotation and translation, and fracture and fragmentation. In this case, it is time-consuming if not impossible to assemble stiffness matrices and reduce them into non-diagonal mass matrices as those normally done in the implicit finite element method. To speed the calculation and reduce the memory use, the central difference explicit time integration scheme is used in the open-source hybrid finite-discrete element method, where no stiffness matrices are assembled or stored. Moreover, the central difference explicit time integration scheme is conditionally stable, where the stability is achieved through reducing the size of the time step, and the accuracy is controlled by the size of the time step (Munjiza, 2004).

However, as pointed out by Mahabadi et al. (2010), it is very difficult for other researchers to use the open-source Y2D hybrid finite-discrete element method since there is no graphical user interface available and the entire input file has to be typed in an ASCII text editor. It may take ages for a novice user to master the naming conventions used for the different databases of control, element, node, property, interaction, and boundary, and set up a model, especially with complex geometry, numerous materials spatially distributed and various initial/boundary conditions assignments. To overcome these shortcomings, a graphical user interface Y-GUI has been developed by Mahabadi et al. (2010) for the Y2D code. Y-GUI can be used to set up models with reduced time compared with that using a text editor, check models graphically, and minimize the possibility of erroneous input files. However, the Y2D code will usually crash as warned by Munjiza (2004) since there is no mechanisms to trace errors. Moreover, Y-GUI is only a pre-processor for setting up and checking models and can't be used to graphically display the analysed results as the M code incorporated in the Y2D code, saying nothing of graphically displaying calculations in real time, which causes significant times are wasted before any errors are recognised. Most important of all, Y-GUI is developed only for the 2D problems and can't deal with 3D problems.

In this paper, an integrated development environment, i.e. Y-2D/3D IDE, is developed for the open-source hybrid finite-discrete element method. Y-2D/3D IDE, as shown in Fig. 1, is written using Visual C++ and OpenGL, which can not only significantly simply the process of building and manipulating the Y2D and Y3D models and greatly reduce the possibility of erroneous model setup but also display the calculated results graphically in real-time. In Y-2D/3D IDE, the Y2D and Y3D codes originally written using C language are rewritten using more powerful and easily understandable object-oriented C++ programming language. Although Munjiza (2004) claimed that Y2D was originally written using C++, only the C-based implementation of the open source Y2D is available to the author. Fig. 1 depicts the Y-2D/3D IDE which is currently under development at Centre for Geomechanics Research, School of Engineering, the University of Tasmania using C++ and OpenGL. The pre-processor can generate not only simple finite-discrete element mesh but also specify the initial conditions, physical properties, contact properties, boundary conditions, fracture criteria, and explosive charges if necessary. However, the more complex finite-discrete element models are usually generated using ABAQUS or Rhinoceros and then imported into the Y-2D/3D IDE for the hybrid finite-discrete element analyses. The post-processor can visually display the calculated stresses, displacements, velocity, force, damage, fracture and fragmentation in real-time graphs. In addition, a number of operations such as pan, rotation, zoom, various viewports in perspective and/or orthographic modes, and slideshow are developed to manipulate the numerical models and calculated results. Several examples are presented in following sections to demonstrate the benefits of the proposed Y-2D/3D IDE.

3 MODELLING OF 2D PARTICLE FLOW THROUGH A DRAW POINT

One of the underground mining techniques is the block caving which consists of an arrangement of extraction points called draw points, organized in galleries forming a lattice and built below the ore, as shown in Fig. 2 a). The extraction of material from the draw points induces a downwards motion of the upper layers creating a flow. This flow contains ore along with significant percentage of undesired useless material called dilution. The dilution is one of the main problem in underground mining because any draw point contaminated with dilution is lost for further ore extraction increasing the mine's operation costs. In principle, a good control of the flow might prevent the contamination of draw points with dilution. It can be achieved by improved understanding of particle flow in block caving. Several scaled experimental and theoretical models have been developed to understand particle flow in block caving. Use of numerical modelling provides an opportunity to enhance understanding of the particle flow law and develop improved methodologies for reducing dilution in block caving. A conceptual 2D model is set up to simulate the particle flow through a single draw point, as shown in Fig. 2. $10 \times 11 = 110$ particles with ellipse shape are placed in a container but positioned as a regular space filling array. The long and short axes of the elliptical particle are 0.3 m and 0.15 m, respectively. The thickness of the container wall is approximately 0.04 m, the width is about 4.4m and the height is about 5.5m. Constant strain triangle elements are used to discretize the particles and the container. The shear modulus of the particles and the container is 110.4 MPa, the Poisson's ratio is 0.17, and the density is 2500 kg/m3. It is assumed that the shear and tensile strength and the fracture energy of the particles and the container are big enough so that no fracture will happen. The viscous damping and contact penalty is 20000 and 1.0×10^8, respectively. The coefficient of sliding friction is 0.3.

The particles are released from their rest positions under a gravitational force that is 100 times gravity in order to reduce the calculation time. The particle flow process is depicted in Fig. 2 b) - j) in terms of distribution of vertical stress at various times. As can be seen from Fig. 2, the initial motion sequence involves the simplest form of deformation, namely translation. It is evident that in this translation no stress is produced, as shown in Fig. 2 a). The particles are then colliding between each other and with the walls of the container and dissipating energy by both viscous damping and the frictional forces. Contact forces were evaluated at each time step, while the central difference explicit time marching scheme was employed to calculate the new velocity fields and new nodal coordinators. It is worth noting that after the considerable movement of the individual fragments, the symmetry of the system is still preserved as shown in Fig. 2 b) - f). The particles then flow through the draw points, collide with the bottom surface of the container, bounce back, and collide with each other (Fig. 3 g - j). Totally, 70,000 calculation cycles are run so that the particles almost rest in the bottom of the container.

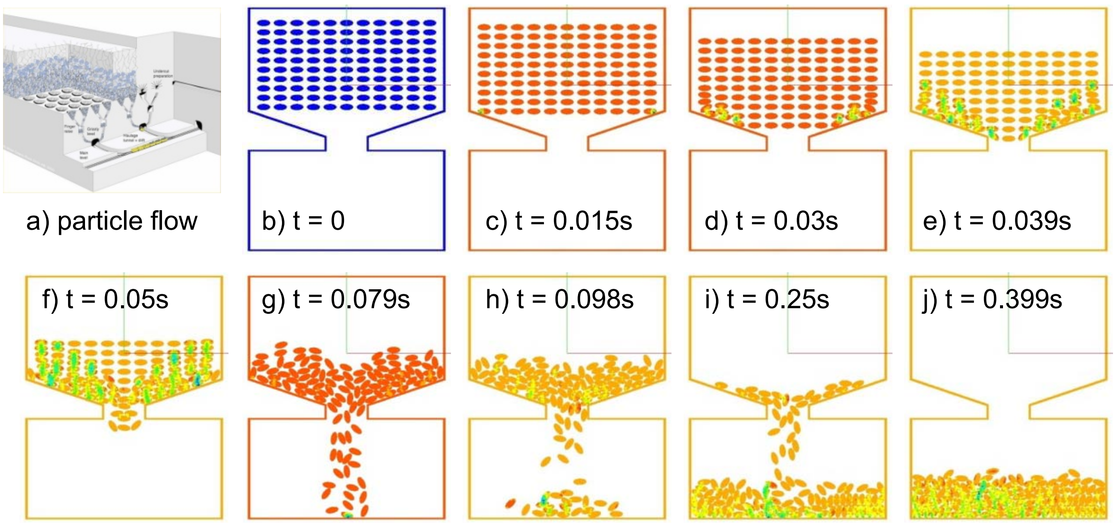

Figure 2. Modelled particle flow process through a draw point in block caving

4 MODELLING OF 3D ROCK FALLING ALONG A STAGED SLOPE

Rockfall poses significant safety hazard for geostructures and personnel in open-pit mining, quarries, and mountain areas. Fig. 3 a) depicts a typical slope in open-pit mining. Over past decades, many experimental and numerical studies have been carried out aimed at understanding the mechanics of rockfall. However, there is still a need to develop efficient numerical models in order to efficiently understand the mechanics of rockfall and control the rockfall hazard. In order to illustrate the capability of the newly implemented Y-2D/3D IDE, a conceptual model is built to simulate falling of three rock particles with irregular shapes along a staged slope similar to that in the open-pit mining, as shown in Fig. 3 b) - h). In the model, the slope, spherical particle, cubic particle, and cylindrical are discretized into 8205, 1674, 583, and 708, respectively, three-dimensional 10-node tetrahedral elements. Thus, there are total 11170 elements and 21818 nodes. The diameter of the sphere is 2m and the characteristic size of the cube and cylinder is 2 m, too. The angle of the slope is 45 degrees. The width of each bench is 2 m expect that of the bottom bench, which is 12 m wide. The length of the slope extends 40 m.

The spherical, cubic and cylindrical rock particles are raised to a height a little bit above the top platform of the slope and then released with an initial velocity of 10 m/s in the horizontal direction. To reduce the calculation time, the acceleration in the vertical direction is set as 100 times gravity. At 17.5 ms, the particles collide with the top bench and cause stress concentrations around the contact area (Fig. 3 b). The stress wave radiate out from the contact area and the particles bounce back into air (Fig. 3 c). Since there is an initial velocity of 10 m/s in the horizontal direction, the particles moves away from the top bench at the same time when moving in vertical direction. At 21.75 ms, the particles collide with inclined slope surface and the second top bench, which, together with the shape of the particles, modify the trajectories of rock falling (Fig. 3 e). The rock particles continues falling alone the slope with the trajectories continued modified by collision and shape (Fig. 3 f - h).

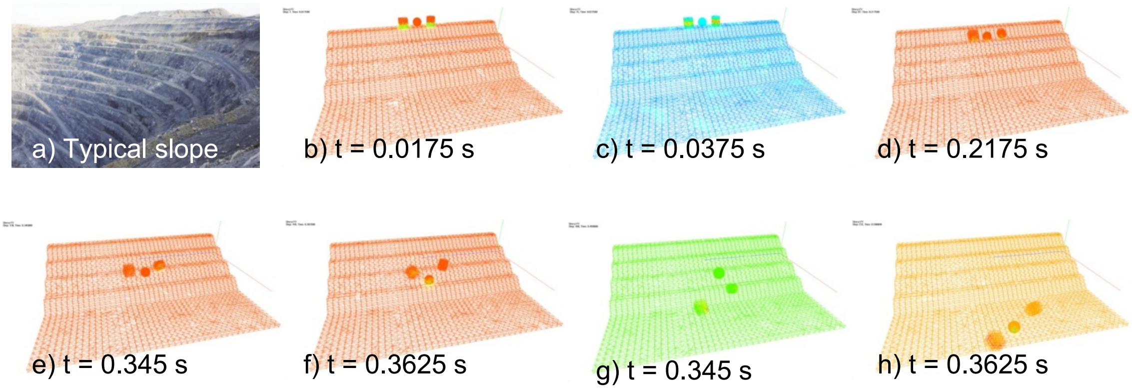

Figure 3. Modelled falling of rocks with irregular shape along a staged slope in open-pit mining

5 MODELLING OF ROCK FRAGMENTATION PROCESS AND RESULTANT FRAGMENT MUCK-PILING PROCESS BY ROCK BLAST

Rock blast has been widely employed in the mining industry for many centuries and it remains a popular method of rock fragmentation to the present day. However, many studies have shown that the situation in current mining production blasting is far from the optimum fragmentation. The space for improving mining production blasting is huge and the economic potential is enormous. Thus the investigation of the fracture and fragmentation mechanism through numerical approaches is essential. This section use the open-source hybrid finite-discrete element method to model rock fracture and fragmentation process and resultant irregular, deformable and fractureable fragment muck-piling process by mining production blast in sub-level caving.

Fig. 4 a) depicts the production blasting in sub-level caving used in LKAB's mine in Sweden, where explosives are placed in boreholes, and the rings are blasted in sequence to recover the ore on each sublevel. Corresponding to the configuration of production blasting in Fig. 4 a), the numerical model is constructed in Fig. 4 b). The length of the boreholes is about 28 m with a diameter of 100 mm. The height of the ring is 30 m and the burden between two neighbouring rings is about 3.5 m. The numerical simulation focuses on the rock fracture in the five rings, which are discretized using dense finite elements. The other 7 m boundaries close the production rings are discretized using coarse finite elements. In order to simulate the rock fragment muck-piling process, a 5 m high drift below the production ring is considered in the model and the bottom of the drift is modelled as rigid and fixed in horizontal and vertical directions. The right boundary of the model is fixed in the horizontal direction since the rock mass may be infinite in mining production blasting. It is assumed that the acceleration in the vertical direction is 100 times gravity in order to reduce the calculation time.

Fig. 4 c) - l) depicts the modelled rock fragmentation process and resultant fragment muck-piling process. The explosives in the left borehole are firstly ignited at 0 ms. Then the detonation wave propagates with a velocity of 5500 m/s upwards. As shown in Fig. 4 c) - d), high compressive stresses are generated in the detonated area and propagate outwards with a wave velocity depending on rock mass properties. The boreholes in neighbouring rings are detonated consecutively with 5 ms delay time (Fig. 4 e - g). Extensive cracks are generated during this process and the rock mass caves in with the accumulation of the cracks under gravity (Fig. 4 h). At about 100 ms, the caved rock mass collides with the bottom surface of the drift and high stress concentrations are generated in the contact area and propagates outward (Fig. 4 i), which results in further fragmentation (Fig. 4 j). The resultant irregular and deformable fragment interact with each other, further fracture if necessary, and muck-piling along the bottom surface of the drift before steady-state is achieved (Fig. 4 k - l).

6 CONCLUSIONS

To conveniently use the open-source hybrid finite-discrete element method, an integrated development environment (IDE) is firstly developed using C++ and OpenGL for the Y2D ad Y3D codes originally developed by Munjiza (2004) and Xiang et al. (2009), respectively. A 2D conceptual model is then built to simulate rock particle flow through a single draw point using the hybrid finite-discrete element method. After that, the hybrid method is implemented to model irregular and deformable 3D rock particles falling along a staged 3D slope. Finally, mining production blast is modelled to demonstrate the capacities of the open-source hybrid finite-discrete element method in simulating rock fracture and fragmentation process, and resultant fragment muck-piling process.

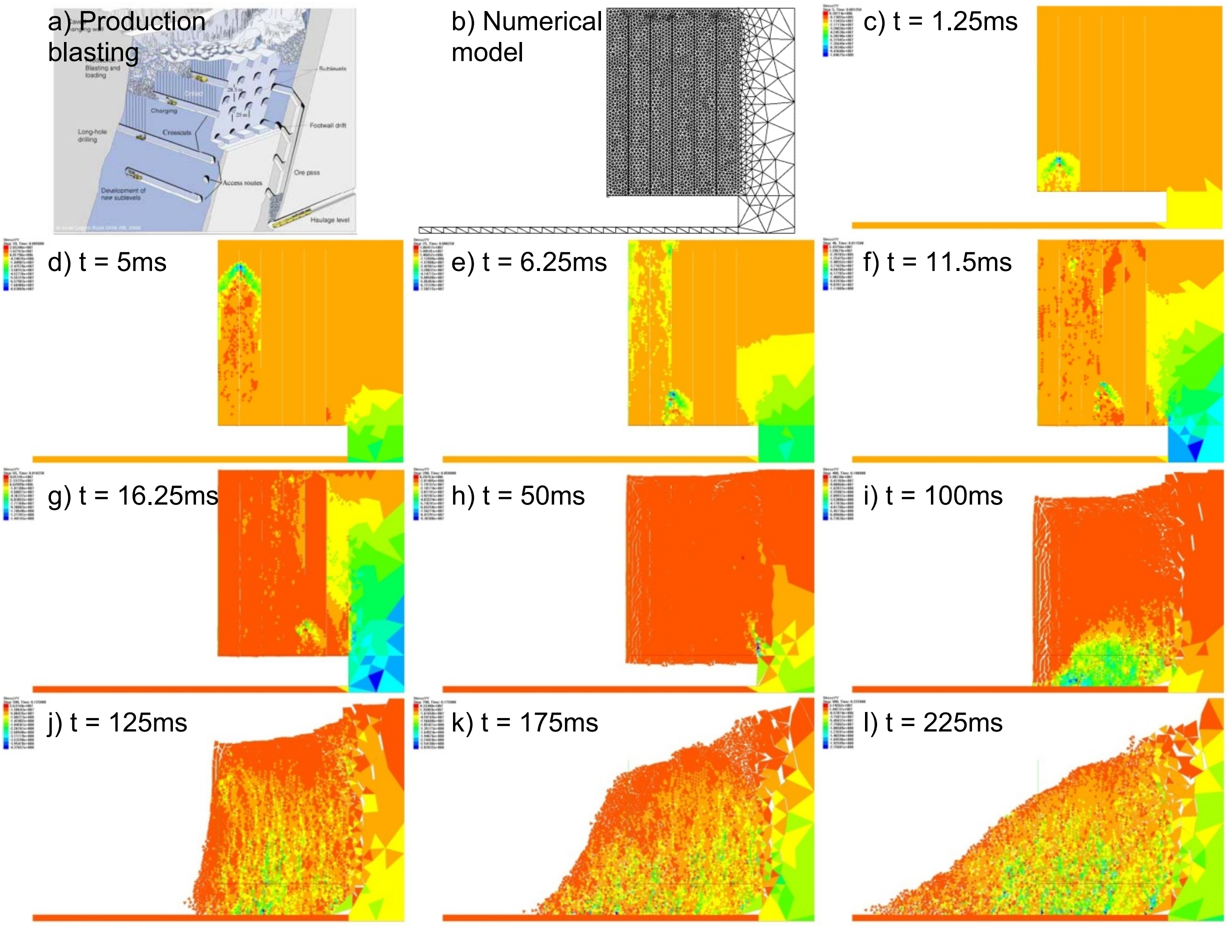

Figure 4. Modelled rock fragmentation and fragment muck-piling by mining production blasting

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