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An airblast hazard simulation engine for block caving sites

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ABSTRACT

In this paper, a weakly compressible Lattice Boltzmann code is coupled with a realistic shape Discrete Element algorithm to create a simulation software to estimate the airspeed happening at airblast events in three dimensions. In an airblast event, air is compressed between falling rocks and the muckpile when the block caving method is used, creating potential hazardous air gusts compromising the safety of personnel and equipment. This work shows how the coupled code is capable of reproducing the key physical layers involved in this phenomenon such as the airspeeds attained by falling bodies in funnel geometries. After some validation examples, the code is used to evaluate the effect of the underground mine geometrical parameters on the potential airspeed. These examples show the potential of the software to be used by mining engineers to estimate accurately the impact of an airblast event.

1. Introduction

Airblast in block caving situations is a very dangerous situation with potential loss of life for operators and damage to mining equipment.[1] Airblasts occur when air pockets are present within the material that is currently being extracted through the drawpoints (Fig. 1).[2] As the material close to the drawpoints (defined as the muck-pile) becomes stagnant, the block falling at the top of the air gap will compress the air. Air will leave the empty space through any potential escape way at very high velocities, potentially endangering personnel and equipment.[3] One fatal example of an airblast accident happened at the Northparkes mine in Australia on November 24th, 1999, where four miners lost their lives.[4]

Airblast prevention has mostly been carried out at the site level by the installation of air obstructing wall structures to reduce the potential rise in airspeed and overpressure.[5] Actions aimed to mitigate effects of a potential airblast accident are difficult to apply at the planning stage due to the lack of appropriate modelling tools to simulate the problem. Modelling approaches have mostly focused on piston models, where the gas pressure is obtained from the adiabatic compression of an ideal gas.[4,6] This has the advantage of being a fast estimate for airspeed and overpressure but it loses the possibility of adding local features to the caving model, such as observation ducts and drawpoints. More sophisticated models use machine learning techniques[7] to analyse and find patterns using global datasets found during airblast monitoring. One promising approach is to use the Discrete Element Method (DEM)[8] to model the rocks being extracted interacting with a Computational Fluid Dynamics (CFD) method representing the air to model the whole process. Recently this idea was used for the first time[9] to obtain important parameters for the air resistance of the muckpile. This study was carried out with circular elements in 2D using the PFC2D commercial code coupled with an incompressible fluid simulation code.

The present study presents a similar approach using DEM, but going a step further by simulating the whole process in 3D including a compressible gas characterized by the air sound speed and particles with more realistic shapes. Furthermore, it will include other cave characteristics such as a number of draw-points and observation ducts. The CFD method of choice is the Lattice Boltzmann Method (LBM), which as will be shown can deal with weakly compressible gases and is easily coupled with the DEM.[10,11]

The paper is structured as follows: Section 2 describes DEM-LBM coupling method in a succinct form and references are given for the readers interested in the details. Section 3 presents a series of validation examples including an experimental case. In Section 4 a parametric study is shown to illustrate the potential of the method to see the effect of different site parameters on a block caving situation. Finally, in

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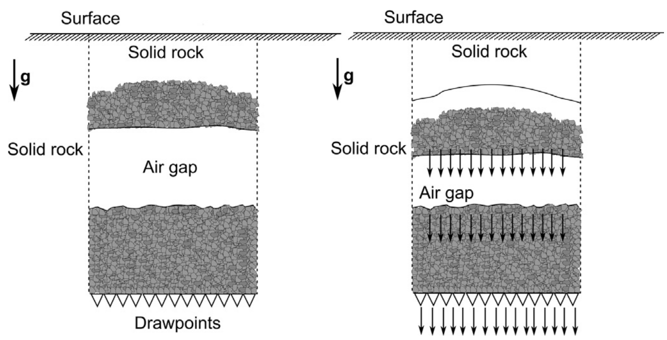

Fig. 1. Airblast hazard. In a block caving mining, the rocks fall down through the drawpoints. In the case there are air gaps between the falling block and the muckpile, the air will be compressed and released through any potential outlet at very high speeds, potentially endangering personnel and equipment.

Section 5 some conclusions and projections of the current work are presented.

2. The method

The simulation approach was introduced by the authors previously in Ref. 11 The fundamentals are based on the spheropolyhedra approach to model contact collision between DEM particles and how it can also be used to simplify the coupling with the LBM code. Here, a brief introduction to the method is included.

LBM is a grid based method solving the discrete Boltzmann equation. It divides the space in a cubic grid of side δ_x.[12] The velocity space is also discretized by a set of velocities $\vec{e}_i$ as seen in Fig. 2. A set of functions $f_i(\vec{x})$ is assigned to the cell centered at $\vec{x}$. These functions represent the density of particles of fluid propagating in one of the different discrete directions. The macroscopic fluid density ρ and velocity $\vec{u}$ are obtained from the following additions over the velocity space,

$$\begin{aligned}\rho(\vec{x}) &= \textstyle\sum_i f_i(\vec{x}),\\ \vec{u}(\vec{x}) &= \frac{\sum_i f_i(\vec{x})\vec{e}_i}{\rho(\vec{x})}.\end{aligned} \tag{1}$$

The discrete form of the Boltzmann equation governs the evolution of the f_i set. This equation contains both the dynamics of collision of particles as well as the transmission of information by streaming at each time step δ_t,

$$\begin{aligned} f_i(\vec{x} + \vec{e}_i\delta t, t + \delta t) &= f_i(\vec{x}, t)\\ &+ (1 - B_n)\left(\frac{1}{\tau}(f_i^{eq} - f_i)\right) + B_n\Omega_i^s,\end{aligned} \tag{2}$$

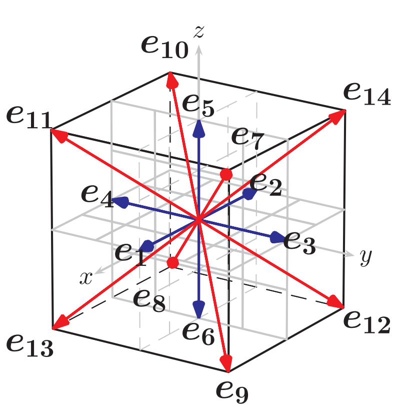

Fig. 2. The LBM cell of the D3Q15 showing the direction of each one of the 15 discrete velocities.

with B_n a volume occupation function which is important for moving boundaries as the ones presented when coupled with DEM, τ is a characteristic dimensionless relaxation time related to the fluid viscosity, f_i^{eq} is an equilibrium function which should be reached at equilibrium conditions and finally Ω_i^s is a collision term representing the momentum exchange with the moving boundary.

Calculating Bn is important to determine to correct momentum exchange with the DEM particles. In[11] it is shown how the form,

$$B_n(\varepsilon) = \frac{\varepsilon_n(\tau - 1/2)}{(1 - \varepsilon_n) + (\tau - 1/2)}, \tag{3}$$

which depends on the fraction of the cell volume occupied by the DEM particle ε_n is suitable. For the momentum exchange term (Ω_i^s) the following form is chosen,

$$\begin{aligned}\Omega_i^s &= [f_{i'}(\vec{x}, t) - f_{i'}^{eq}(\rho, \vec{v}_p)]\\ &- [f_i(\vec{x}, t) - f_i^{eq}(\rho, \vec{v}_p)],\end{aligned} \tag{4}$$

where i' is the direction opposite to the $i - th$ direction and $\vec{v}_p$ is the velocity of the DEM particle at that point. With these two terms calculated, the force

$$\vec{F} = \frac{\delta_x^3}{\delta_t}\sum_n B_n\left(\sum_i \Omega_i^s\vec{e}_i\right), \tag{5}$$

and the torque over the DEM particle,

$$\vec{T} = \frac{\delta_x^3}{\delta_t}\sum_n\left[(\vec{x}_n - \vec{x}_{CM}) \times B_n\left(\sum_i \Omega_i^s\vec{e}_i\right)\right], \tag{6}$$

are similarly calculated by summing the individual contributions over all the occupied cells where $\varepsilon_n > 0$.

As introduced by Chen and Doolen,[13] to recover Navier Stokes (NS) equations, the equilibrium function must be,

$$f_i^{eq} = \omega_i\rho\left(1 + 3\frac{\vec{e}_i\cdot\vec{u}}{C^2} + \frac{9(\vec{e}_i\cdot\vec{u})^2}{2C^4} - \frac{3u^2}{2C^2}\right), \tag{7}$$

where $C = \delta_x/\delta_t$. This version of LBM allows small changes in density and in fact can be used to model compressible gases as long as low Mach numbers are reached. In fact, the form for the equilibrium distribution will give a well defined relation for the fluid pressure p as a function of the density ρ in the NS equation,

$$p = \frac{C^2}{3}\rho, \tag{8}$$

where the factor 3 comes from the discretization of 15 velocities shown in Fig. 2. This implies that the speed of sound $Cs = C/\sqrt{3}$. Furthermore, it will be shown that it is practical to use this equation for situations where the gas is compressed by working with changes in pressure $\Delta p = Cs^2\Delta\rho$, where the changes are relative to an equilibrium pressure and density values. By this equation, it can be seen that once δ_x is fixed by the desired resolution, then the time step δ_t must be chosen to obtain a realistic speed of sound. In this study $Cs = 340\ m/s$ which in some cases imposed small values for δ_t making some simulations challenging in terms of computational time.

One last property of the fluid is the kinetic viscosity ν related to the relaxation time τ by

$$\nu = \left(\tau - \frac{1}{2}\right)\frac{\delta_x^2}{3\delta_t}. \tag{9}$$

Once δ_x and δ_t are defined by the speed of sound, the ν can only be controlled by the value of τ. However, it is a well known fact that for low viscosities $\tau \sim 1/2$ and the method becomes unstable. One very successful technique to avoid this instability and obtain an accurate response is to use the Large Eddy Simulation scheme within LBM.[14] In it a second viscosity is added to the one obtained from Eq. (9) to account