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A Review of Particle Percolation in Mining

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Abstract

Understanding particle flow is crucial to the success of block and sublevel caving operations. Even though the gravity flow of caved rock has been studied almost since caving methods were introduced, its mechanisms are still far from understood. One key aspect of gravity flow that has the potential to significantly accelerate dilution ingress is the percolation of fine particles. Although percolation has many forms, in mining, percolation predominantly occurs during shear when fine particles are exposed to the void structure of the coarse matrix, allowing fines to find and percolate through the voids between coarse particles. Therefore, it is believed that percolation of fine particles has the potential to significantly affect dilution, segregation and overall ore recovery in sublevel and block caving.

Particle percolation occurs in many large scale particle assemblies composed of geomaterials. Examples include rock piles, tailing dumps, retaining walls, block caves and sublevel caves. Because of the scale of these systems, very little experimental data has been collected to understand and validate the mechanisms and parameters controlling fine particle percolation. This paper reviews the percolation in mining, with reference to relevant findings by other researchers in related disciplines.

1 Introduction

The phenomenon of particle percolation is found in many areas, such as ore and waste rock drawing in caving mines, mixing of different size particles in cement or sand, in foodstuff ingredients, electronics applications and even in fertiliser industries. Percolation theory originated in the work of Broadbent and Hammersley (1957) where physical models were used to study the flow of fluid in a porous medium, with randomly blocked channels. Subsequent to this work, percolation attracted the attention of physicists and pure mathematicians interested in the fundamental mechanisms of coupled particle-fluid interactions. These fundamental works have been complemented by a large number of small and large scale experiments by engineers and many remarkable findings have been reported on real-life percolation phenomena.

Numerous papers have been published dealing with the foundations of flow and transport through porous media in the civil engineering field. On the other hand, chemical engineering has focused on the development of conceptual models on the theory of mixtures. The emergence of percolation theory has provided probabilistic models for systems where the connectedness properties of some components dominate the behaviour emerged on the theoretical physics and stochastic analysis (Hornung, 1996).

In sublevel and block caving mines, segregation phenomena can arise from percolation induced by gravity and vibration (Mosby et al., 1996). This phenomenon is important as the flow characteristics dictate the shape of the volume and affects the overall recovery and dilution (Just and Free, 1971; Chen, 1997; Pretorius, 2007). Hence it is vital to understand the mechanism of percolation as it significantly affects the flow characteristics of ore in ore pass systems (Hadjigeorgiou and Lessard, 2007), dilution and eventually the efficiency of the caving method. In addition, Beus et al. (1999) identified several potential safety problems relating to the ore and waste rock hang-ups such as structural failures, blocked gates and water flow and, in addition, air blasts can occur as a result of poor understanding of particle flow of ore and waste rock. Also, percolation of fine particles from ground water transport is a key factor in mud rushes.

Although the study of particle percolation in chemical engineering (and associated engineering disciplines) has continued now for 50 years, there is essentially no validated theory developed for large scale systems such as those encountered in block and sublevel caving. Efforts to understand these systems are restricted by data limitations, where even relatively basic parameters such as fragmentation cannot be easily measured or modelled. As a result, further research is required to understand the mechanisms of percolation and, in particular, percolation rates. In this context, a number of key motivations exist for improving our understanding of percolation. The first relates to situations where there is the potential for fine waste to enter drawpoints. Here, one example is caves located below exhausted open pits, where pit slope failures, perhaps initiated by the cave, have the potential to transport fine particles into the glory hole, which then percolate to the drawpoints, resulting in increasing dilution. Fine particles could be highly weathered material from the surface, mill and mullock waste dumped into the pit. A second example is the interaction with existing workings such as sublevel caves or open stoping operations. Here the sublevel cave voids, or the open stope could contain backfill or highly comminute material. A final example is the generation and subsequent percolation of fine particles from within the caving rock mass. For example in weak sedimentary rocks, faulted or altered zones may comminute, producing fine particles.

In each of the above examples there is almost no validated theory or data, either from scaled physical models, numerical models, or site based data, which can be used to forecast the generation and movement of fine particles. Therefore, percolation theory is a problem that is in principle easy to define however, not so easy to solve, and is in general imperfectly understood (Stauffer, 1985; Khakhar et al., 1999).

2 Percolation in granular flow

The flow of granular media occurs across a range of industries, such as the transport of coal, ore, sand, powders, food and many more. A detailed discussion on selected aspects of gravity flow in mining applications is presented by several authors (Just and Free, 1971; Chen, 1997; Rustan, 2000). Just and Free (1971) described the flow characteristics of the broken material (both ore and rock waste) and their importance to overall recovery and dilution in a sublevel caving mining system. Chen (1997) proposed a modified stochastic model to better predict the draw shape of rock fragment flow. Rustan (2000) reviewed the importance of gravity flow of broken rock and recommended concentration on coarse blasted rock phenomena.

Castro (2006) repeated experiments previously undertaken at 1:30 scale by Power (2004), at 1:100 scale and presented findings that contradicted Powers assertion that mean particle diameter was the principal control on isolated extraction zone width. As found by previous authors back to Kvapil (1965), Castro found that, based on physical modelling results, the mass drawn and the column height are the major parameters controlling the geometry of the drawzone. However, due to uncertainty on scaling of qualitative results obtained from physical models and a lack of reliable data from full scale tests, calibration works are still necessary in order to fully validate these findings. Castro (2006) also used the purely kinematic cellular automata theory previously presented by Muller (1996), to study isolated and multiple drawpoints in block caving.

The relatively poor understanding of granular flows and ore extraction from a caving rock mass is currently an area of concern in industry and research (Melo et al., 2007a; 2007b). Granular flows can be quite complex and in general are not well understood (Campbell, 1990; Hutter and Rajagopal, 1994) and generally modelling is a difficult task (Jaeger et al., 1996). In addition, the parameters of rapid gravity flows have been hard to adequately describe because of experimental and analytical difficulties (Hutter and Scheiwiller, 1982). This often leads to production problems and inefficient or ineffective equipment in industries that process granular materials. Research in percolation in granular flow is motivated by numerous applications encountered in industrial processes. For example in geophysics, percolation studies were devoted for the description and prediction of natural hazards such as landslides, rock avalanches and pyroclastic flows (Forterre and Pouliquen, 2008).

One of the main issues in particle flow study is the lack of constitutive equations (Goldhirsch, 2003). Since most granular materials handling systems behave unpredictably (and in some cases are irreproducible) it is a vital to better understand the statics and dynamics of granular flow (Goldhirsch, 1999). In recent years, significant efforts have been made into the modelling of granular flows using continuum mechanics approach (Tardos, 1997; Karlsson et al., 1999). Continuum models assume that granular media behaves as a fluid. Some continuum theories adopt a complex mathematical approach and are limited to representation of spherical granular particles. Although these models are partially successful in capturing some characteristics of the flow, they do not incorporate information on particle micro-mechanics, which influence the material parameters (Christakis et al., 2002). This is crucial as these findings are needed to model the various interactions between different particles or particles with their surrounding environment. As a result, they are not able to simulate processes that are of great importance in mining applications (i.e. hopper filling/ emptying, ore handling and conveying), where these interactions lead to phenomena such as particle size segregation (Christakis et al., 2002) and dilution in an ore draw zone.

Discrete models are conceptually much simpler but rely heavily on computing power, especially when modelling the large scale systems (Hogue and Newland, 1993). On the other hand, micro-mechanical models are able to successfully describe the flow of granular media by accounting for various types of interactions at the microscopic level (Baxter et al., 1997; Yang and Hsiau, 2001). However, these models can only be applied to a small number of discrete particles, due to the complexity of the simulated processes. Therefore, such models are inappropriate for the modelling of large-scale processes, unless idealisations can be made. This is due to the limitations on the number of particles and restrictions on the computing time required for the simulations to be completed.

Almost all granular materials consist of particles of varying sizes, densities and/or shapes. These differences in particle properties may induce segregation upon handling process and others' processes (Ottino and Khakhar, 2000). Salter et al. (2000) indicated that outcomes of these phenomena during the central filling of a hopper can lead to a situation where the majority of the fines congregate at the middle of the hopper and may have a dramatic effect on further operation in the process.

As been recognised by several researchers, percolation is an important factor in segregation (Bridgwater et al., 1969; Tanaka, 1971; Bridgwater and Ingram, 1971; Drahun and Bridgwater, 1983; Mosby et al., 1996; de Silva et al., 2000; Duffy and Puri, 2002). In particular, Drahun and Bridgwater (1983) suggest that the one percolation mechanism is due to the size and density effect in a moving free surface of a bulk material. In this case fine particles may move downwards causing the segregation process to occur. Recently, it was assumed that percolation is the predominant means by which segregation will occur during hopper discharge (Ketterhagen et al., 2008).

There is very little research devoted to percolation in mining applications. Most of work on percolation has emerged in powder applications (Bridgwater et al., 1969; 1978; 1985; Bridgwater and Ingram, 1971; Scott and Bridgwater, 1975; 1976; Cooke et al., 1978; Cooke and Bridgwater, 1979; Drahun and Bridgwater, 1983). During this period of years, Bridgwater and his team performed a number of experiments to provide insight into fundamental processes controlling the distribution of components in a free flowing powder and/ or of agglomerates in a cohesive one. Later, this was reviewed and expanded by Savage (1987) and Bridgwater (1994; 1995).

It is interesting to highlight that all the previous studies have resulted in one essentially similar finding. They concluded that both the diameter ratio of coarse to fine particles, and the associated density ratio, significantly affects the rate of percolation during a shearing process. It was also found that fine particles tend to percolate through a bed of coarse particles during a shearing disturbance. However, Foo and Bridgwater (1983) reported that sometimes the motion of large particles in a failure zone (region of high strain) was towards that of greatest strain rate. This has made the percolation study more complicated and unsolved.

2.1 Percolation of fine particles

Percolation of fine particles (as shown in Figure 1) occurs in mixtures of different particles sizes were exposed to the perpendicular of shear deformation and paralleled gravity force (Duffy and Puri, 2002). During shear, fine particles are exposed to the void structure of the coarse matrix, allowing fine particles to find and drop through suitable voids in the coarse particle layer (Johanson et al., 2005). Whenever a mixture of particles of different sizes is disturbed in such a way to rearrange the particles, percolation of fine particles can occur. Disturbance can arise from the existence of shear within the mass, caused, for example, by stirring or by pouring the particles into a heap or even when a mixture is shaken (Williams, 1976). Percolation can also take place when a particle bed is vibrated (Williams, 1976).

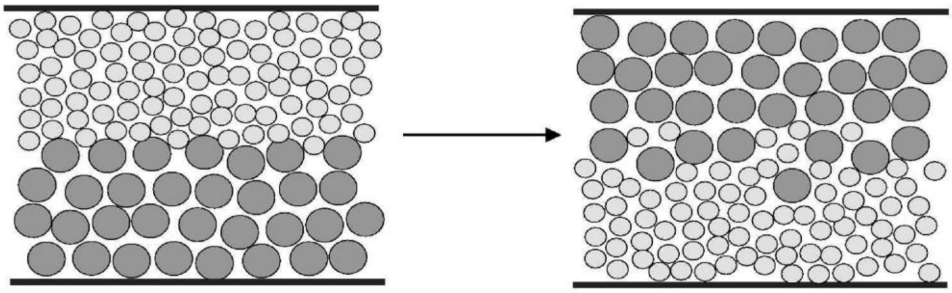

Figure 1 Percolation segregation (Li, 2005)

Scott and Bridgwater (1975) have studied the rate of percolation of small particles in a simple shear cell in which the bed is subjected to a uniform shear strain. By reversing the direction of movement of the cell, unlimited strain can be applied. They found that difference in particles size was the most significant cause of percolation. They showed that the percolation velocities observed could be explained in terms of the diffusion equation.

Johanson et al. (2005) found that if the fines are less than one-third the size of coarse particles and free flowing, they may percolate through the coarse matrix of particles resulting in sifting segregation. While if the particle shapes are different, then the internal friction angles of individual components may be different, resulting in angle of repose segregation (Johanson et al., 2005).

2.2 Mechanism of percolation

Pierce (2004) noted that for particles that are smaller than the minimum interstices between larger particles, percolation can occur spontaneously while particles that are larger than the minimum interstices may only percolate if the bed is disturbed in some way (e.g. through shearing).

According to Cooke et al. (1978), a dimensional analysis of percolation velocity, u, for a small sphere percolating through larger spheres can be write as Equation (1):

$$\frac{u}{\dot{\gamma} d_b} = f\left\{\frac{d_p}{d_b}, \frac{\sigma_y}{E_b}, \frac{E_p}{E_b}, \frac{d_b \rho_b g}{E_b}, \frac{d_b \dot{\gamma}^2}{g}, \frac{\rho_p}{\rho_b}\right\} \tag{1}$$

Where:

u = mean downward velocity of percolating particle (m/s)

$\dot{\gamma}$ = strain rate (s^{-1})

d_p and d_b = the percolating and bulk particle diameters respectively (m)

E_p and E_b = Young’s modulus of the percolating particle and the bulk particle respectively (N/m^2)

σ_y = normal stress on the top surface of the cell (kg/ms^2)

g = acceleration due to gravity (m/s^2)

ρ_p and ρ_b = the percolating and bulk particle densities respectively (kg/m^3).

Base on Equation (1), Cooke et al. (1978) found that percolation velocity is controlled principally by the size ratio, d_p/d_b while σ_y/E_b is a measure of particle deformation under the applied normal stress. The influence of the ratio of percolating to bulk particle deformation, E_p/E_b under applied stress is slight. $d_b\dot{\gamma}^2/g$ is a measure of the time for a particle to fall through a gap to the lifetime of the gap while the group of $d_b\rho_b g/E_b$ may be negligible as it is a measure of bulk particle deformation under its own weight. The dimensionless factor of $u/\dot{\gamma}d_b$ decrease as normal stress rises and it was found that $u/\dot{\gamma}d_b$ increased at low strain rates. Bridgwater et al. (1978) found that if the diameter ratio of particle-to-bulk, d_p/d_b are between $0.269 \leq d_p/d_b \leq 0.673$ the

$u/\dot{\gamma}d_b$ ratio significantly decreased. ρ_p/ρ_b is the ratio of the weight of the particle and increase in ρ_p/ρ_b will slightly raises $u/\dot{\gamma}d_b$ (Cooke et al., 1978).

Table 1 shows a number of control parameters on percolation rate highlighted by Bridgwater et al. (1978); Drahun and Bridgwater (1983) and Pierce (2004). Of all control parameters, the particle diameter ratio and rate of strain has the largest effect on percolation rate compared to others. On the other hand, increasing of the strain rate, $\dot{\gamma}$ above 0.4 s^{-1} does not affect the percolation velocity but increases the value of the intercept on the particles. At the high value of interception on the particles, the gaps that form between coarse particles will have less possibility for a longer opening thus decrease the probability of a fine particle to pass through an underlying gap. In addition, Pierce (2004) found that in general, materials with greater density and lower elastic modulus displayed a higher percolation rates. It is also notable that for non-spherical materials; shape factor are need to be considered as this factor may have significant influence on percolation rate (Cooke et al., 1978).

Table 1 Parameters controlling percolation rate

Description	Comment
Particle diameter ratio	Largest effect compared to other controlling parameters
Rate of strain	Percolation rates are faster below 0.4 s^{-1}
Normal stress	An increase in the normal stress reduces the percolation velocity
Particle density	Higher density particles percolate faster than lower density particles
Material properties	Particles with low elastic modulus percolate faster than higher elastic modulus
Surface properties	Smooth and shiny surfaces percolate faster than rough and scratched surfaces
Shape properties	Rounded shape percolate faster than angular shape
Wall effects	Smaller particles percolated more rapidly at the wall than in the bulk

3 Methods to simulate particle flow of broken rock

Both physical and numerical modelling has advantages and disadvantages when attempting to predict the mechanisms of particle percolation in caving. For example, one disadvantage of physical modelling is that the costs of construction and time constraints relative to the immediate needs of an active mine often limit the usefulness of physical modelling (McNearny and Barker, 1998). By contrast, the advantage of numerical modelling (in systems small enough to be studied) is that all field variables can be measured and mechanisms quantified for a wide range of particle parameters and model geometries. However, numerical modelling of particulate systems is still developing, and real data from working mines is required for validation of modelling results.

3.1 Physical modelling

As stated previously, percolation mechanisms have been studied by simple shear apparatus developed for testing soils (Scott and Bridgwater, 1975; Bridgwater et al., 1978; Johanson et al., 2005). Bridgwater and Ingram (1971) and Bridgwater et al. (1978) developed a simple shear apparatus (called Mark IA, IB, IIA, IIB, III, IV and V) that induced percolation. This simple shear cell operated by moving a bed of particles in a back and forth direction as illustrated in Figure 2. This develops a uniform strain which enables the percolation rate to be found without recourse to exhaustive sampling or cine photography (Scott and Bridgwater, 1975). By using this simple shear apparatus, a bed of particles was sheared so that its shape changed from a rectangular to a parallelogram and thus analogous to a failure zone (Cooke and Bridgwater, 1979). The failure zone is defined as a thin layer between two groups of particles, in which there is considerable motion (Bridgwater and Ingram, 1971).

Percolation rates were established by measuring the mean time taken for particles fed to the top of the cell to transverse the cell and fall out at the bottom. Percolation rates were then measured from the slope of the linear relation found between residence time and bed height, thus eliminating end effects (Cooke and Bridgwater, 1979). The linear relationship also implies that the behaviour of the material in the cell is independent of position and that the percolation velocities deduced are true material properties (Cooke et al., 1978).

Through a series of experimental works, percolation velocities are found to increase with increasing shear rate and decreasing size of the smaller particles. It is also postulated that the percolation rate depends mainly on total strain, the relative sizes of large and small particles and also on rate of strain, even at low strain rates (Scott and Bridgwater, 1975). In addition to that, most of the work done by Bridgwater and his team focused on powder systems and its application to mining scale granulates remain to be undertaken.

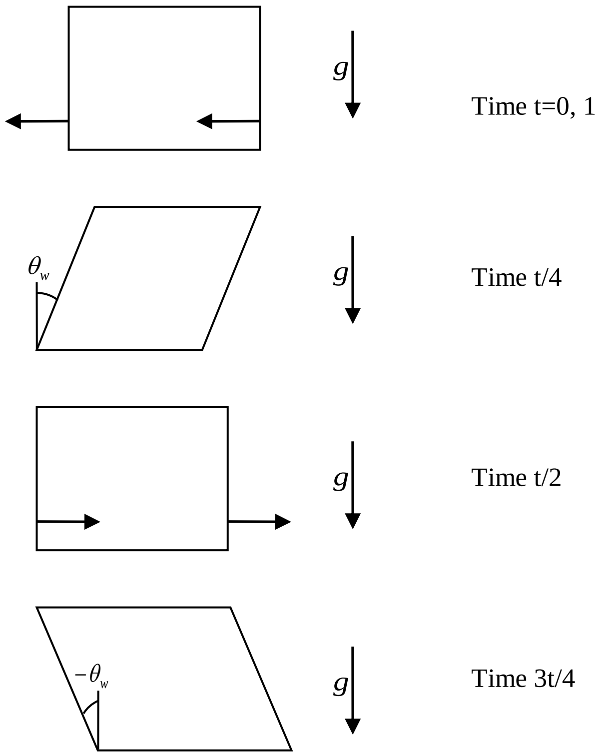

Figure 2 Principal mechanism of motion imparted to particles by the simple shear cell (Cooke et al., 1978)

Hsiau and Shieh (1999) constructed a shear cell device (Figure 3) with adjustable lower wall velocity with a 3 mm average diameter glass bead. Image processing technology and a particle tracking method were employed to measure the average and fluctuation velocities in the streamwise and the transverse direction. It is found that the diffusive displacement of tracking particles were the highest in the high-shear region and significantly decreased with the rate of shear imposed. However, since the experiments were limited to being two-dimensional (2D), it could not genuinely represent actual percolation in a typical mining scenario.

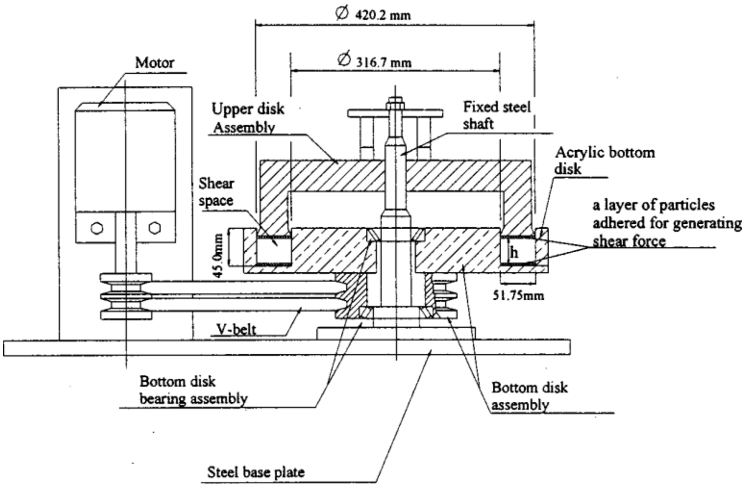

Figure 3 Two-dimensional shear cell with adjustable lower velocity (Hsiau and Shieh, 1999)

Subsequent to their previous work using a vertically oriented shear tester device, Duffy and Puri (2002) have designed the Primary Segregation Shear Cell (PSSC) as shown in Figure 4. By changing the cam connected to a variable speed motor, this tester was capable of applying up to 25% strain. The effects of size ratio, strain, cycle speed and bed depth on the particle percolation were evaluated. It is postulated that size ratio was the most dominant variable that affects the percolation rate of fines through a bed of coarse particles compared to others. However, since this work used a mixture of spherical glass beads it could not fully characterise actual shape of granular materials in cave mining environment. Spherical glass beads are probably good approximations for sand particles, which, although angular on the surface, are still roughly spherical in shape and become more so as collisions break off any protuberances.

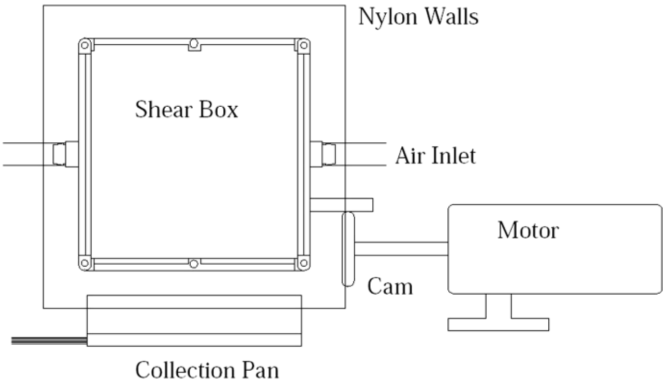

Figure 4 Overall schematic of vertically oriented primary segregation shear cell (Duffy and Puri, 2002)

Johanson et al. (2005) built a simple shear box with a dimension of 130 mm (L) x 130 mm (H) x 50 mm (D) to measure the magnitude of sifting segregation occurring in bulk material. This design was similar to one attributed to Scott and Bridgwater (1976) and Stephens and Bridgwater (1978) for measurement of a single particle through a bulk assembly of material.

By using this simple shear box device, the total shear, γ in the box is computed from the maximum extension angle, θ_w (as illustrates in Figure 2) of the side walls and the number of cycles, N given by Equation (2):

$$\gamma = 4N\tan(\theta_w) \tag{2}$$

A complete shear cycle consist of starting with the end walls perfectly vertical and moving the bottom plate left until the end wall forms an angle with the vertical of θ_w. Once this maximum extension is achieved, the strain direction is reversed and strain is continued until the maximum extension angle $-\theta_w$ is reached (Figure 2). Finally the bottom piston is moved to the position where the end walls are completely vertical and another cycle is started (Johanson et al., 2005). It is concluded by this experiment that sifting segregation can be modelled as a velocity dispersion term that depends on local concentration, total strain and the available void space.

However, the use of sand particles (350 μm materials sandwiched between two layers of 1650 μm sand) does not represent the actual cave mining environment. It is noted that granular materials resulting from crushing or caving are generally highly angular (Campbell, 1990). Since the sand particles tend to behave (and become) more spherical than angular, the finding may not be consistently reliable. Yenge (1980) noted that the flow of caved ore could not be described satisfactorily by theories developed for the flow of other materials, such as sand, because the particles sizes, discharges rates and boundary conditions in the mining problem were not analogous to those of other cases. Nevertheless, the simple shear box apparatus used in this work has shown a potential approach to differentiate between the angle of repose segregation or percolation process.

3.2 Numerical modelling

Several difficulties remain in realistic modelling of rock particle flow, such as determining shape functions, damping factors, and the relative stiffness characteristics of the rock particles and the confining walls (Beus et al., 1999). However, computer simulations have been shown to be a powerful tool in the investigation of granular flows (Campbell, 1989; Savage and Dai, 1993; Rosato and Kim, 1994; Pierce et al., 2003) especially the discrete element method (DEM) (Jing and Hudson, 2002; Ng, 2005). DEM is a conceptual departure from finite difference methods. On the other hand, kinetic theory has also been successfully applied to mathematical model the constitutive relation for flowing granular materials (Shen and Sankaran, 2004).

Dolgunin et al. (2003) has divided mathematical models of rapid shear flows into two groups. The first group is models formulated in terms of continuum theories, which are based on different forms of the relations between the stress tensor and the strain rate tensor. The second group is models based on micro-structural analysis, which evaluate stresses as function of momentum transfer by collisions of particles.

Based on a works by several researchers, Chen (1997) has categorised numerical/mathematical models of granular materials flow methods into three groups:

- Analogue models involving the identification of draw volume geometry.
- Force-acceleration and stress–strain analysis based on fundamental physical laws.
- Stochastic theories and probability studies.

An analytical model (ellipsoid theory) based on experimental results proposed by Kvapil (1965) has been widely applied in caving mine design and draw volume estimation due to its simplicity. However, it only deals with the geometry of gravity flow and provides little insight into the caving mechanism. In comparison, a stochastic model has an advantage over this approach, as it provides a better description of the stochastic processes of granular material flow. However, its application to practical caving mine design is limited as there is some discrepancy between the draw shape predicted by the stochastic model and that obtained by physical models (Chen, 1997). The other difficulty with existing stochastic models relates to the fact they are usually purely kinematic, which means they consider only the movement of objects without any consideration of the stresses or forces placed upon them. As a result the development of shear bands and the horizontal movement of material cannot be captured in existing approaches.

To date, a number of numerical models have been developed such as UDEC3D, PFC3D, CAVESIM and REBOP. Masliyah and Bridgwater (1974); Savage and Dai (1993) and Campbell (1997) employed computer tools and numerical analysis to study shearing of granular flow. Shinbrot et al. (1997) applied stochastic models with validation of numerical simulations. In present work, Rahman et al. (2006) employed the DEM simulation in their particle percolation study. The DEM approach (Cundall and Strack, 1979; Guest and

Cundall, 1995) offers a vast opportunity in visualising and understanding the mechanisms of percolation, because DEM provides insight into the microstructure of the granular material. DEM simulations have been found to produce realistic macroscopic behaviour under conventional drained or undrained compression simulation and also under more general loading conditions (Ng, 2005).

Some success in the modelling of rock flow has been made through the application of cellular automata methods. The first application of a three-dimensional (3D) cellular automata to caving is documented in Sharrock (1999). The method has subsequently been calibrated to large scale physical modelling tests, marker trials data, and anecdotal evidence of flow at a large number of sublevel and block caving operations. A description of this work is available in Sharrock (2003; 2008) and Sharrock et al. (2004). Percolation has been included as a model parameter, but these models rely on the assumptions listed in this paper from previous work in chemical and civil engineering, which require further development and validation from actual caving and targeted experimental studies.

PFC3D (Itasca, 1999; 2005) operates using DEM methods offer some advantages such as ability to simulate a wide variety of granular flow situations and allows a more detailed study of the micro-mechanics. PFC3D employed an explicit time-stepping algorithm hence it can continuously monitor the evolution of key parameters during the flow process (Pierce et al., 2003). Nevertheless, due to computational capability this method is still limited to a relatively small number of particles and generally limited to spherical particles due to the increase in computational cost with increasing complexity of geometry.

Based on replication of Bridgwater et al. (1978) experiments, Pierce (2004) used PFC3D to study a series of simple shear tests on mixtures of coarse and fine spherical particles in caved rock. By using two-particle clumps to replace single sphere particles in vertical shear tests, it is found that the influences of particle shape are minimised. It is also indicated that the percolation rate is not significantly influenced by shearing direction while reducing the strain rate significantly increases the percolation rate of fine particles. The potential of PFC3D approach to replicate the mechanisms involved in shear-induced percolation are promising. However, many efforts are still required to develop reliable results especially to replicate appropriate large scale tests. In addition the particle shape assessment applied in this work was limited to two-particle clumps only.

It is interesting to highlight that sphericity has been assumed in most studies for many reasons in numerical modelling. This is because it is easy (in theoretical work and computer simulations) to detect a collision of circular particles, as particles are in contact whenever their centre are two radii apart (Campbell, 1990). However, granular materials that result from crushing or mining operations will generally be highly angular, and pellets of extruded plastics will often have a cylindrical shape (Campbell, 1990). Yet all the analyses and most of the computer simulations have been performed for perfect spheres or disks. Thus, the main issue arising from the use of circular discs (in 2D) or spheres (in 3D) in numerical simulations (or even in physical experiment) is the excessive freedom of the particles to rotate compared with real soil particles (Powrie et al., 2005).

Some authors claim, that at the present level of monitoring technology, it will under no circumstances be possible to fully calibrate an entire numerical model of a real cave (Guest, 2007). However, the authors of this paper believe that, based on available data, it has not been proven that reasonable calibration cannot be achieved, if reasonable quality fragmentation and marker data is available.

4 Conclusion and recommendation

In summary, knowledge of percolation mechanisms has very general application in minerals processing, mining, geology and civil engineering. Since particle percolation in mining is not fully understood, but is significant, this area offers exciting challenges for improving caving designs in the future. This new knowledge has the potential to help mining operations identify and avoid dilution hazards and optimise ore recovery.

The study of particle percolation has been employed in various contexts. Most of these are still far from providing an understanding of the percolation of particle mechanisms in caving. While, it is no doubt best to obtain percolation data from full scale tests, these are expensive, time consuming and the parameters of interest are difficult to measure. Numerical / mathematical models have been shown to be a powerful tool for this purpose, but these remain largely invalidated due to the lack of reliable data. Moreover, some of the numerical models rely heavily on computing range and time especially when modelling the large-scale systems.

Physical modelling is still relevant and this can be done by modelling the particular process at the appropriate scale. Even though it is not practical to model every mechanism by a single device or approach, it is believed that, if a specific mechanism can be identified that explains the majority of percolation taking place (Duffy and Puri, 2002).

Much work is still required to identify percolation mechanisms and forecast percolation in caving mines. Based on our review, particle shape, size, void infill rates, and transport properties such as shear strains within the fragmented rock mass are perhaps the most important factors to be considered in future numerical and physical modelling studies of mining processes.

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