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Experiments and simulation of gravity flow in block caving through FlowSim

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Abstract

In block caving, gravity flow plays a key role as it influences ore recovery and dilution. Recent research at the University of Chile has been directed towards expanding the understanding of gravity flow through experiments that could be included in gravity flow simulation tools. FlowSim BC is a rapid simulation tool for gravity flow for long-term block caving planning purposes, which is based on the cellular automata approach. This approach has flexibility to incorporate observed flow mechanisms through unique local rules, which are applied to a discrete media that emulates the caved rock. The mechanisms used in developing FlowSim have been obtained through controlled experiments and mine data analysis. In this paper, the authors present a summary of new understandings obtained through experiments and field data, and the methodology used to calibrate the new mechanisms included in FlowSim. The results indicate that the complexities of gravity flow in block caving applications can be modelled, and that this type of modelling tool can be used effectively for mine planning purposes.

Keywords: *block caving, gravity flow, mine planning*

1 Introduction

In underground cave mining methods, modelling the ore resources and the subsequent gravity flow of the caved rock is fundamental to accurately define a given mine production plan. In recent years, a considerable amount of development has been advanced towards the application of new mathematical approaches for modelling flow behaviour. Tools include discrete element methods (DEM), finite element methods (FEM), mechanistic and cellular automata methods (e.g. Cundall et al. 2000; Castro 2006).

FlowSim BC is a numerical tool to simulate the gravity flow of caved rock using the cellular automata (CA) approach (Castro 2006; Castro et al. 2009, 2016; Valencia 2014; Fuentes 2015; González 2016). This type of modelling approach was selected because it is simple to implement in computers and can be used to simulate the extraction of many drawpoints (a hundred or more). Its main disadvantages are that it does not simulate the physics explicitly, and it requires observations to calibrate the transition function.

FlowSim is based on the numerical method of CA, which is a system of cell objects with the following characteristics:

- *Grid/space* – The equally sized cells are discretised in blocks having a dimension of 2 × 2 × 2 m, which is the maximum block size.
- *State* – Each block could have one of three states: granular, solid or void. In the granular state, blocks can move while their density is equal to the solid density of the rock mass. In the solid state, blocks cannot move even if there is space to fall into. Void blocks have zero density, and are generated at the drawpoints by the draw process. The state of a block may change from granular to void and from solid to granular. In FlowSim, a parameter C_{ijk} represents the state of each block

placed in a specific location (ijk) within the grid. C_{ijk} may have the value of -1, 0 or 1 which shows the solid, granular or void state, respectively.

- *Neighbourhood* – This is the basic cell arrangement around a void cell where the transition function is applied (Figure 1).
- *Transition function* – This local invariant mathematical rule is applied during the simulation for the movement of blocks. FlowSim applies two different transition functions; one for unconfined or surface flow (material at the repose angle outside the drawpoint), and the other for confined or gravity flow (associated with the movement of particles generated by the space created by other in-contact particles). The transition function for gravity flow is defined by the flow probability using the following equation (Valencia Vera 2014):

$$P_i = \frac{{d_i}^{-n} \times {RF_i}^{-m}}{\sum_{k=1} {d_k}^{-n} \times {RF_k}^{-m}} \quad (1)$$

where:

d_k = distance between the void cell and the cells in the top level.

RF_k = rock flow parameter which is related to the flow characteristic of the block. This variable takes a value 100 for coarse fragmentation and 10 for fine fragmentation.

n = adjustment constant related to the overall flow behaviour of the caved rock. Increasing this parameter leads to a narrower movement/extraction drawzone.

m = preferential flow parameter related to the potential for fines migration (blocks with a lower RF value). The larger the value of m, the larger is the probability of fines migrating to the void.

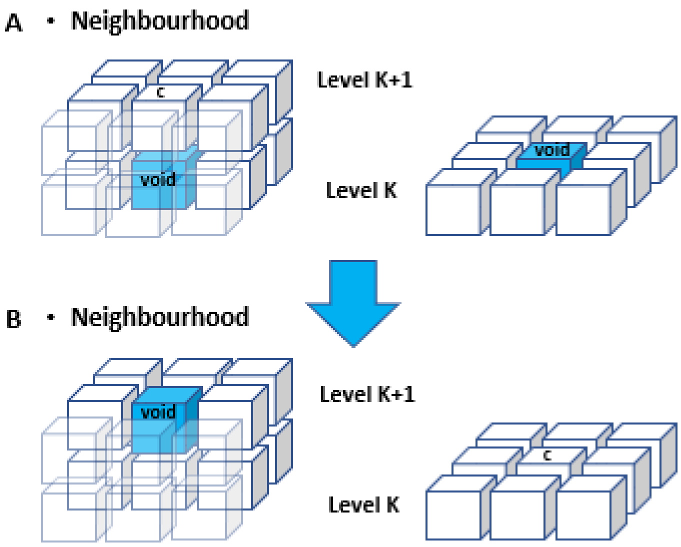


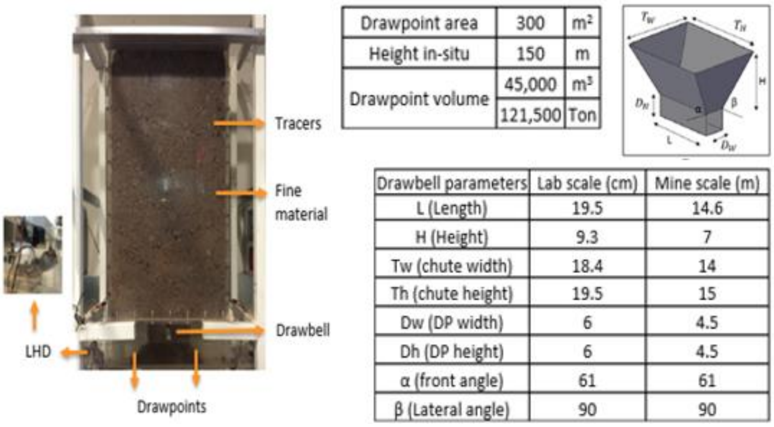
Figure 1 Schematic view of the neighbourhood blocks and upward moving of the void cell; (a) Before extraction; and, (b) After extraction

It should be noted that the transition function is only applied if there is a minimum number of voids (Cv). This parameter restricts the voids' diffusion process, and it is related to the swell factor. If Cv = 0, then the voids will migrate upwards without restriction and the swell factor is zero. This mechanism has been demonstrated to replicate the evolution of the movement zone as shown in experiments (Castro 2006).

The main challenge is how to calibrate the parameters. In the next sections, the know-how and the methodology for calibrating the parameters is presented.

2 Extraction zone diameter

The diameter of the extraction zone (IEZ) is related to the fragmentation of the caved rock; the finer the fragmentation, the smaller the extraction zone diameter. Previous experiments using gravel have shown that for coarse fragmented rock (d_{50} = 0.6 m), the extraction zone diameter could reach 28.5 m at 100 m draw (Castro 2006). However, for fine fragmentation (d_{100} < 0.3 m), there were few experiments to quantify the drawzone diameter. To obtain data for fine fragmented rock, laboratory experiments were conducted on a physical model (scale 1:75) using an emulated load–haul–dump (LHD) system for the draw (Sanchez 2017). Figure 2 shows the geometry and parameters of the physical model.



Drawpoint area	300	m²
Height in-situ	150	m
Drawpoint volume	45,000	m³
	121,500	Ton

Drawbell parameters	Lab scale (cm)	Mine scale (m)
L (Length)	19.5	14.6
H (Height)	9.3	7
Tw (chute width)	18.4	14
Th (chute height)	19.5	15
Dw (DP width)	6	4.5
Dh (DP height)	6	4.5
α (front angle)	61	61
β (Lateral angle)	90	90

Figure 2 Experimental set-up built to characterise fine granular material (DP = drawpoint)

Table 1 shows the experimental results. It can be noted that the IEZ is smaller than for coarse rocks and that the ratio between the IEZ and Dw for fine fragmented rock reaches 2.86 (Sanchez 2017).

Table 1 Flow zone parameters for fine fragmented rock obtained from experimental data (scaled values)

Parameter	Data
Fragment size	< 0.37 m
IEZ diameter	12.9 m
Drawpoint width (Dw)	4.5 m
IEZ/Dw	2.86

In FlowSim terms, parameter ‘n’ controls the flow behaviour, therefore, it is linked to the IEZ.

Figure 3 shows the behaviour of the diameter of the drawzone for different values of n based on experimental data. Thus, small values of n (n = 3–4) are related to coarse fragmentation (d_{80} = 1 m) and large values of n (n > 9) are related to the flow of fine fragmentation (d_{100} < 0.3 m).

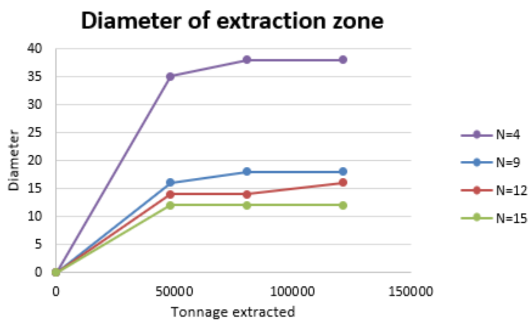
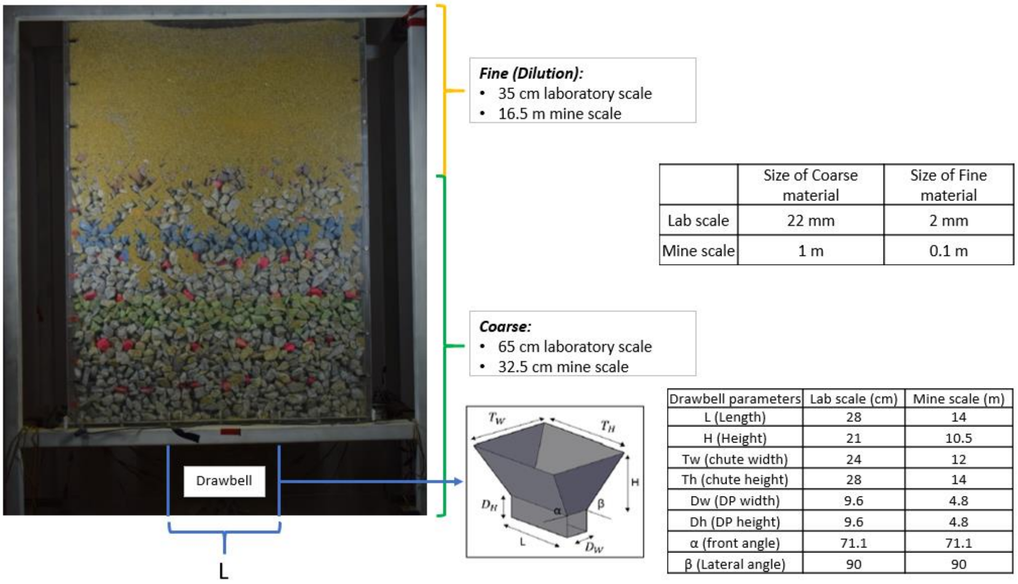


Figure 3 Simulated IEZ in FlowSim by varying the parameter of flow parameter n

3 Fine fragmentation flow modelling

3.1 Fines migration

Fines migration, or percolation, is known to be an important aspect of gravity flow. However, the amount of experimental work published on this aspect is scarce. Physical scaled model tests (scale 1:50) were conducted to study the fine migration phenomenon (Figure 4). In this, a box was filled with two distinct materials in terms of fragmentation. The base was filled with coarse fragmentation (having a d_{80} = 1 m) followed by a layer of fine material above it (d_{80} = 0.1 m). Therefore, the ratio between the coarse and the fine fragmentation is 1:10.

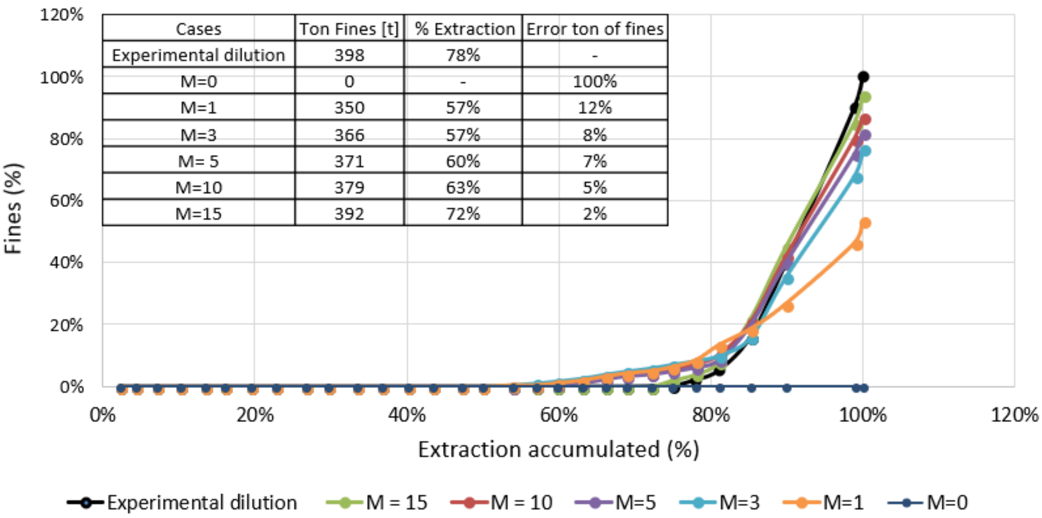


	Size of Coarse material	Size of Fine material
Lab scale	22 mm	2 mm
Mine scale	1 m	0.1 m

Drawbell parameters	Lab scale (cm)	Mine scale (m)
L (Length)	28	14
H (Height)	21	10.5
Tw (chute width)	24	12
Th (chute height)	28	14
Dw (DP width)	9.6	4.8
Dh (DP height)	9.6	4.8
α (front angle)	71.1	71.1
β (Lateral angle)	90	90

Figure 4 Experimental set-up for fines migration experiments (Arancibia 2018)

Fines migration experiments were quantified in terms of two observations; the point at which fines reach the drawpoints and the increase in the amount of extracted fines with draw. In terms of simulations in FlowSim, the parameter that intervenes in the fines migration is 'm'. The larger the m value, the more chance there is for fines to migrate. As noted in Figure 5, it is possible to obtain the fines' entry point and the amount extracted in the experiments for m = 15. Considering Equation 1, the fines would have a large probability of moving downwards.



Cases	Ton Fines [t]	% Extraction	Error ton of fines
Experimental dilution	398	78%	-
M=0	0	-	100%
M=1	350	57%	12%
M=3	366	57%	8%
M= 5	371	60%	7%
M=10	379	63%	5%
M=15	392	72%	2%

Figure 5 Comparison between experimental result in physical model and FlowSim BC v5.0 simulation in terms of percentage dilution entry and fines extracted

3.2 Preferential flow

The RF and m parameters could be useful to quantify, in terms of a production plan, the effect of caving and flow moving towards preferential zones as depicted in Figure 6. These preferential zones for caving could be due to the presence of structures or low-strength materials.

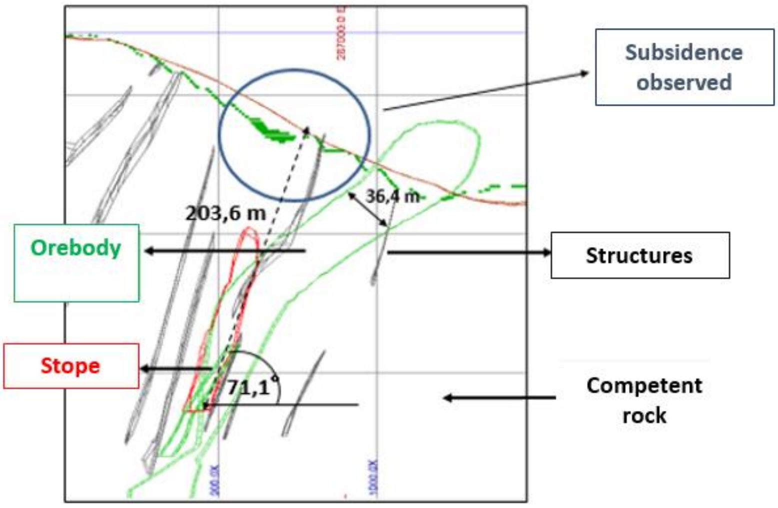


Figure 6 Profile view showing the inclined caving propagation

The results of the FlowSim using the fines migration logic applied to a sub-vertical structure are shown in Figure 7. As indicated, the caving and flow in this case are not vertical but driven by a structure of low strength where the cave propagated preferentially.

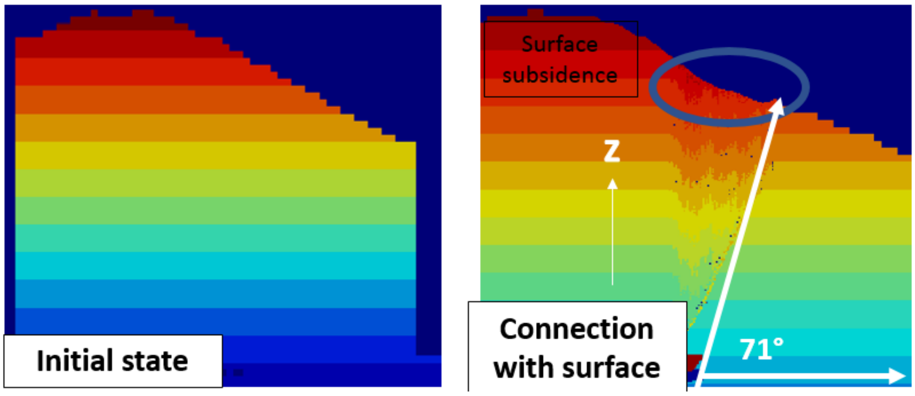


Figure 7 FlowSim calibration for preferential flow, emulating the inclination and the area where subsidence occurred

3.3 Mixing of fines and coarse materials

The above discussion and results consider the flow for fines and coarse materials separately. However, it is well-known that the small fragmentation controls the flow when reaching a certain limit in terms of volume (Kvapil 2008). To experimentally quantify the influence that fine material and humidity have on flow, confined gravity flow experiments were conducted (Olivares 2014). Olivares (2014) carried out these experiments for different moisture levels (from 0, 3, and 6%), percentage of fines (0, 20 and 40%) and vertical load (0, 1.5, 3, 6 and 10 Mpa). Fines have a d_{80} = 0.1 mm, while coarse fragmentation reaches d_{80} = 15.6 mm. The results indicated that an increase in the vertical load implies a decrease in the flowability of the material (Figure 8).

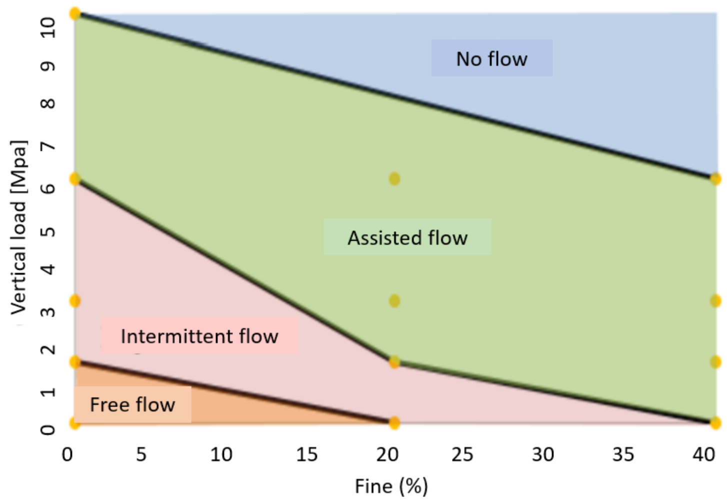


Figure 8 Effect of presence of fines and vertical load in flow conditions

In the case with a large presence of fines (about 20%) at the extraction points and the presence of moisture (6%), it was concluded that the fluidity of the material would be drastically diminished because the flow behaves like fine material.

Based on the above experiment, FlowSim also incorporates the influence of the mixing of fines and coarse fragmentation on the overall flow behaviour (Figure 9). When two different flow materials are found, the transition function uses the larger n value if the percentage of fine fragmented rock is above 30%.

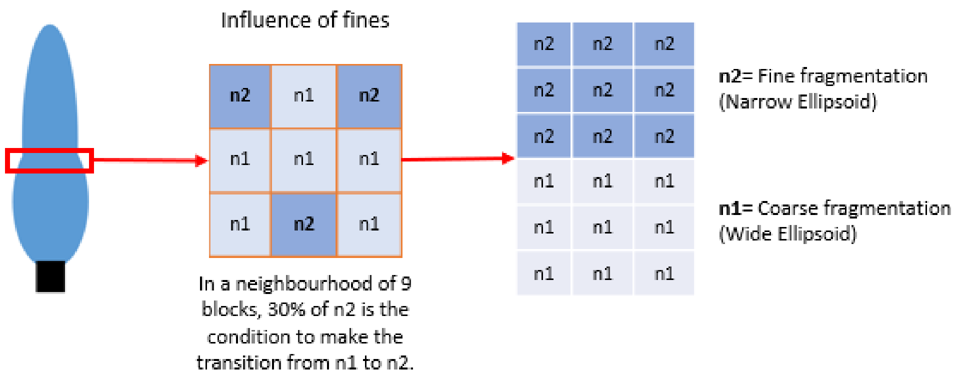


Figure 9 Influence of fines to change the flow behaviour

4 Caving and rilling

Cave back assessment and modelling is key in block cave mining as it influences safety, the stability of mining infrastructure, and the control of dilution due to the trajectory of the propagation. In FlowSim BC v5.0, the cave back shape has been included by considering the state of the block during the simulations (Guzman 2018). For example, there are blocks in solid state that could change to granular in a given period. This allows the places within the column where flow could occur to be restricted. Figure 10 shows the simulations' results after applying this restriction. As shown, the results indicate that FlowSim could emulate the main characteristics of a block caving system (rilling, airgap, and porosity in the caved rock) as postulated in the conceptual model described by Brown (2003).

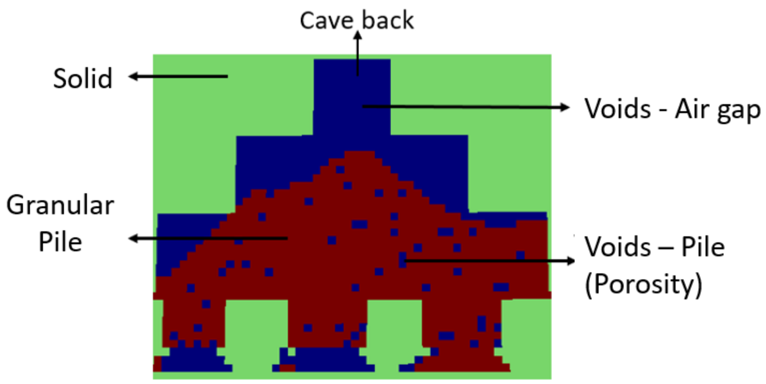


Figure 10 **Representation of the new states generated by FlowSim BC v5.0 (brown = solid rock that could flow; green = solid rocks that cannot flow; blue = voids)**

The key parameter that controls the airgap and the rilling potential in FlowSim is Cv, which is related to the caved rock swell factor. As shown in Figure 11, a larger Cv results in a smaller airgap volume.

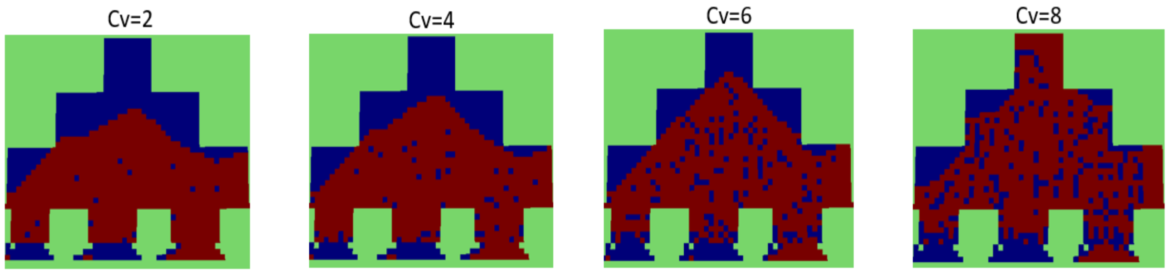


Figure 11 **Airgap volume in terms of porosity which is controlled by Cv in FlowSim BC v5.0**

The density of the caved rock is related to the solid density and porosity:

$$\rho_{ap}[\frac{kg}{m^3}] = \frac{\rho_s[\frac{kg}{m^3}]}{1+Porosity} \quad (3)$$

Figure 12 shows the relationships between both Cv and porosity, and Cv and density of the caved rock. It is well-known that coarse fragments have a larger swell factor than fine fragmented rock. This also has implications in terms of potential rilling; the smaller the swell factor, the larger the airgap and the space for surface flow or rilling.

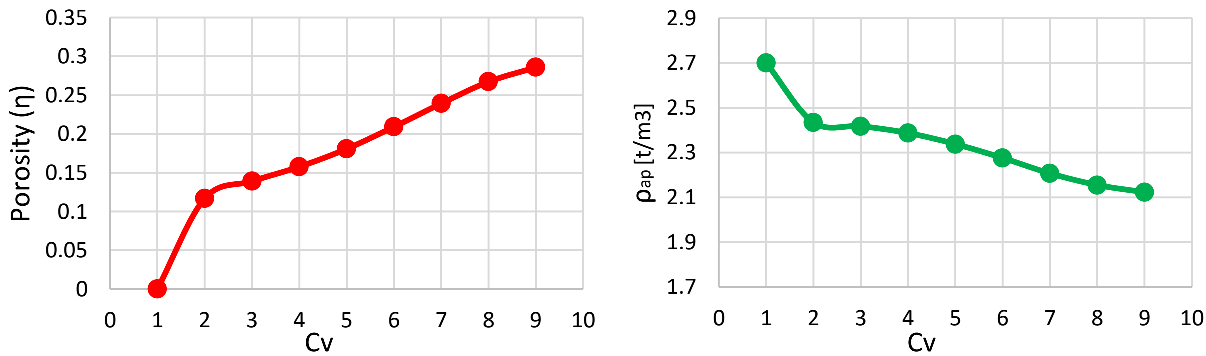


Figure 12 **Variation of porosity and density as a function of Cv**

In FlowSim, surface flow considers the friction angle. This is applied within the cave back and at the surface, as shown in Figure 13.

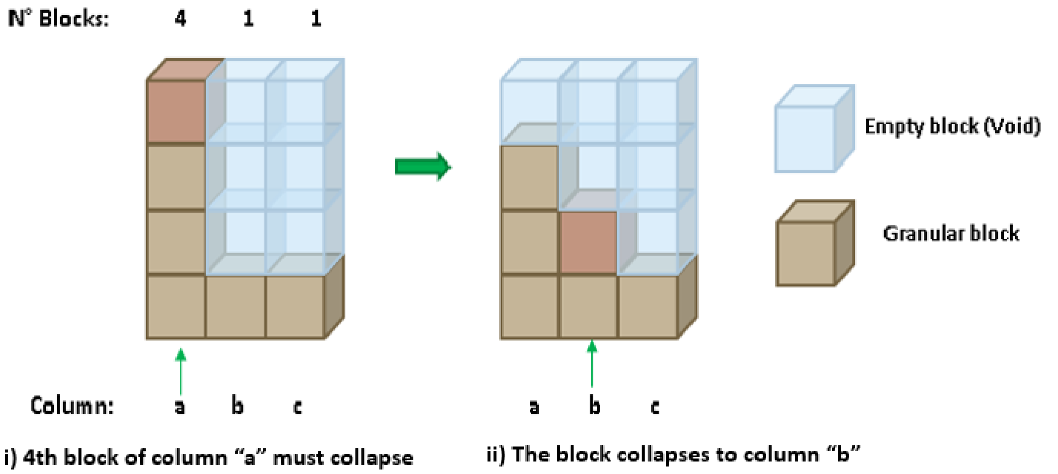


Figure 13 Rilling mechanism

The addition of surface flow and cave propagation could result in significant horizontal movement of caved rock. Horizontal movement of markers has been observed in caving mines (Altamirano & Castro 2018). Figure 14 shows an example of the results of extracted marker simulations with and without cave back and rilling, so these are apparently key features for mine planning purposes as they can determine what the ore reserve could be at a drawpoint level.

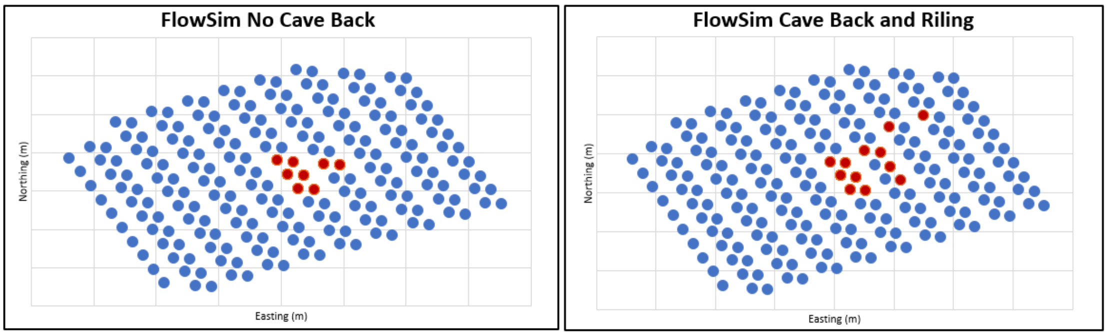


Figure 14 Simulations of gravity flow including cave back and rilling

Finally, Table 2 summarises the main results of the study. As noted, the parameters of the transition function are related to the fragmentation and the fines migration and preferential flow mechanisms. While the flow zone diameter and fines migration have been set, there is still work to be done to obtain the swell factor parameters from field data.

Table 2 Summary of the main parameters for FlowSim calibration and its physical meaning

FlowSim parameter	Function on simulations	Typical values according to experimental and mine-scale calibrations
n	As n increases, the diameter of the extraction zone narrows. Therefore, n is related to fragmentation of the material.	n (coarse, d_{80} = 1 m) = 4 n (fine, d_{80} < 0.3 m) = 10–15
m	As m increases, a higher probability for fines migration or preferential flow is achieved.	m = 0; for no preferential flow. m = 15; in case of a clear preferential or fines migration.
Cv	This is related to the swell factor of the caved rock. A small Cv means a small porosity and a large potential for horizontal movement due to draw.	Cv is to be adjusted according to the swell factor and airgap.

5 Conclusion

FlowSim BC v5.0 is an innovative block cave mine planning tool that has been developed rigorously from experiments and observations of gravity flow in the field. The simulations show qualitatively many of the observed phenomena in caving such as caving propagation, airgap, surface rilling and fines migration. In terms of quantitative results, errors can be as low as within a 3% range when calibrated to experimental or mine data. It is expected that this type of tool could replace some ruled-based approaches and will continue to improve as more understanding of gravity flow is gained through experiments and mine data.

Acknowledgement

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