Quantifying effect of concurrent draw on extraction zones in block caving mines using large scale 3D physical model

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There remains a debate within the literature and among practitioners of caving methods as to the effect on draw zone geometry for the concurrent drawing of multiple drawpoints. Concurrent draw refers to an extraction schedule where a limited amount of material is drawn from each drawpoint before moving to the next drawpoint to draw the same amount. One hypothesis concludes that the flow geometries of a single drawpoint increase while another assumes no change from that of isolated draw. The largest 3D physical model constructed using gravel as the model media has been used to further investigate interactive draw of extraction zones as part of an International Caving Study (ICS) and Mass Mining Technology Project supported by major international companies with interest in caving methods. All extraction zones were measured in 3D. To date a maximum of 10 drawpoints have been modelled. Model results so far indicate no growth in the horizontal width of extraction zones using concurrent draw. Experiments conducted with multiple drawpoints that were spaced less than the width of isolated extraction zones showed that the combined horizontal area of draw appears to reduce with the increasing overlap of isolated extraction zones. The horizontal widths of extraction zones continued to increase within the height of the draw tested.

Keywords: Gravity flow, Granular materials, Multiple drawpoints interaction, Block caving, Physical modelling

Introduction

In large scale underground metalliferous mining methods, and in particular for caving mining methods, the characteristics of gravity flow of broken ore and waste rock in addition to draw management practices control the amount of valuable material recovered, the extent to which it is diluted by waste rock. Gravity flow characteristics also influence decisions on extraction level layout, in particular the spacing and location of drawpoints. All these have a large impact on the economics of mining.¹

Many factors are known to influence flow behaviour in caving environments. These include initial design factors, operational factors, and the natural gravity flow properties of broken rock.² Knowledge of the natural flow properties of rock and how these are influenced by design and operational factors is a prerequisite for optimal extraction and/or production level design.

There is currently debate within the literature of caving methods as to whether or not the consecutive

draw from adjacent drawpoints influences the behaviour of broken rock under flow. Researches conducted in physical models have shown that the zones that define the extraction zone and movement zone increases due to the drawing of multiple adjacent drawpoints.^{3-6,8}

This paper describes the results of an experimental programme using the largest 3D physical model ever constructed to study the gravity flow of broken rock in a mining environment. An experimental study of the interaction of extraction zones for a range of drawpoint spacings is described and preliminary conclusions made relative to the effect of concurrent draw on ore recovery and dilution.

Previous work

In understanding and quantifying the flow of broken rock, there are two main concepts describing the shapes formed by material moving and extracted in granular flow.⁷ The first of these is the limiting outline that defines the original location of material that has been drawn from a drawpoint at any given point in terms of mass, i.e. the extracted material. The second concept is the limiting outline that defines the boundary between stationary material and material that has moved from its original location at a given extracted mass, i.e. the material under flow.

Various authors have referred to these shapes in different ways in the literature. The shape that defines

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1 Movement and extraction zones when point of draw is worked in isolation (left): mass flow as consequence of interaction of movement zones when drawpoints are spaced at distance d

the original location of the extracted material has been defined in various places as the ellipsoid of motion, draw ellipse, the draw body, the draw envelope, the ellipsoid of draw or the isolated draw zone. The authors will use the term isolated extraction zone (IEZ) in this paper. The shape that defines the limits of material that has moved has been called, among other things, the limit ellipsoid, the loosening ellipsoid, the ellipsoid of movement, the movement envelope or the draw zone. The authors use the term isolated movement zone (IMZ) in this paper. Figure 1 illustrates these concepts for drawing material from a single drawpoint in isolation from other flow zones.

In block caving mines ore is drawn from multiple drawpoints in accordance with some predefined draw sequence depending on the local draw control strategy. Current design guidelines in caving mines are based on the interaction of isolated movement zones in ideal draw conditions.^{5,8} The production level layout and the distance between drawpoints (d in Figure 1) should allow the ore/waste interface to move in mass in order to avoid early dilution. As a result of mass flow most of the ore will be extracted with minimal dilution as ore/waste boundary will be lowered uniformly.

It has been possible, albeit in a limited number of cases, to measure IEZs at the mine scale in sublevel caves.^{9–11} However, because of the greater complexity of block caving, the determination of IEZs in practice has not been possible to date. Current understanding of extraction zones in isolation has been largely based on studies on physical models.^{3,4,10,12,14} Studies of the geometry of extraction zones under multiple drawpoints have indicated that under the draw of multiple drawpoints the flow characteristic of gravel changes. Peters³ observed extraction zones in a 2D gravel model and concluded that when drawpoints were spaced at a nominal distance of 1.14 times of the average IEZ at full height the overlap of extraction zones occurred. An expansion of extraction zones due to the drawing of multiple drawpoints (in this case 2) was thus concluded. However, only a very limited number of experiments were carried out by Peters and no dispersion in IEZs was measured. The observed expansion of IEZs concluded by Peters could therefore be a result of dispersion rather than a change in extraction zone geometry due to the drawing of multiple drawpoints.

Marano⁴ observed in 3D sand models that the combined movement zones of a number of drawpoints

2 Physical model (ladder shown is 6.5 m long)

were larger than in isolated draw. Interaction of IMZs was found when drawpoints were spaced up to $1.5 \times \text{IMZ}$. Laubscher has proposed design criteria based on Marano's conclusions of critical interaction limits for movement zones.^{5,8} In view of that the authors investigated the geometry and interaction of movement zones, which found contrasting results than Marano's.¹² Based on this finding, it is necessary to investigate the geometry and interaction of extraction zones as these zones define material that is drawn from the drawpoints, which is the topic of this paper.

Three-dimensional physical model

The physical model was designed to run simulations of flow for block caving mines under both isolated draw and interactive draw conditions. Variation of design parameters such as drawpoint spacing and block height were also allowed for under this design. Under the block caving interactive draw zone configuration the physical model had the internal dimensions of $3.5 \times 2.5 \times 3.3$ m (width $\times$ depth $\times$ height), and held approximately 55 tonnes of aggregate (see Fig. 2). This represents the largest 3D physical model ever constructed to study flow using gravel as the model media.

The physical model was set to geometrical scales of 1:30, and then reduced into 1:100 with respect to current design practice. Model height was 3300 mm, which represented a block of 100 m high scaled (in 1:30 scale) and 330 m high scaled (in 1:100 scale).

In the 1:30 scale model, drawpoints were 120×100 mm (width $\times$ high) (3.6×3.0 m at that scaled dimensions) and open into a drawbell with vertical brow and minor apex angle of 68.6° . These dimensions are based on a drawpoint and drawbell design used at the

CODELCO's El Teniente 4 South mine in Chile.¹³ The height of the drawbell above the floor of the drawpoint was 500 mm (15 m scaled) while its width was 433 mm (13 m scaled).

In the 1:100 scale models, drawpoints were 36 × 30 mm (wide × high) (3.6 × 3.0 m at that scaled dimensions). The decision to reduce the scale to 1:100 was to enable models to simulate a more realistic block height, as the 1:30 model was only able to simulate a maximum block height of 100 m which is far below the height in current mines (130–500 m). This model was also able to investigate the geometry of an IEZ that is surrounded by other IEZs under interactive draw, which was not possible at a scale of 1:30. This made the model closer to a real mine condition, and simulation of the Esmeralda block in El Teniente Mine in Chile was carried out, which will be explained in detail in the sections on 'Isolated draw' and 'Concurrent draw from 10 drawpoints'. The authors carried out investigation on this change of scales and found no observed distortion between them.¹⁴

No drawbell was used in this model due to practical reason. Power¹⁰ demonstrated that the drawbell does not have effect upon the geometry of IEZ.

The methodology used to carry out experiments is described in a previous publication.¹⁴

Model assumptions

The following assumptions and simplifications were made to study the interaction limit of IEZs in block caving through physical modelling:

- (i) it is assumed that the rock mass has caved; in this context, the rock mass could be considered a granular mass composed of non-cohesive and coarse fragments that flow slowly towards the drawpoints under the action of gravity
- (ii) the granular mass is characterised through its size, shape and angle of friction and could be considered heterogeneous (composed of large and fine particles) and isotropic
- (iii) the granular flow occurs in a 3D environment
- (iv) as particles flow to drawpoints, some rock breakage occurs through abrasion but it is negligible
- (v) the geometries of the flow zones at different geometrical scales in the large physical model are comparable as long as the materials have an equal friction angle and particle shape.

Materials and instrumentation

The material used in the experiments was crushed phyllite from a local quarry. The gravel was air dried before being used in the experiments. This had the objective of avoiding cohesion due to capillary effects on the material's fine fraction as it was found that results of the physical model might be able to be scaled up to *in situ* scale as long as the material is non-cohesive.¹⁵

At a geometric scale of 1:30, a wide distribution of gravel size was used, which intended to match an *in situ* distribution. The particle size distribution is shown in Fig. 3. If scaled up, the gravel represents broken rock of a mean size of 0.54 m, with a maximum size of 1.2 m, which represents a relatively coarse cave fragmentation.

The aspect ratios appear to be similar for all gravel sizes, the characteristic shape being long relative to the width and wide relative to the depth (length/width 1.6

3 Particle size distribution of 1:30 model media

SD=0.4, length/height 2.8 SD=1.4, width/height 1.7 SD=0.9). Tests to determine the shear properties of the gravel were undertaken in a large diameter shear box. The normal loads used in the tests ranged between 15 and 65 kPa to match those within the physical model. A mean friction angle of 45° was noted.

At a scale of 1:100, the media did not have a wide distribution as in the 1:30 model and the mean particle size was smaller, 7 mm. The reason for this was due to the size of the drawpoint in this model; fragments larger than 20 mm could not be used since it would create hang-ups. However, it was demonstrated that the width of draw was controlled by the mean particle size, not the distribution.¹⁰ When scaled, it represents 0.7 m fragment size, which is a typical mean size of caved ore in modern block caving mines. The aspect ratio was similar with the media in the 1:30 model. The friction angle of the model media was similar to the 1:30 scale at 44°.

Measurement of extraction zones was undertaken through back analysis of recovered labelled markers, as described in a previous publication.¹⁴

Model experiments and results

A number of experiments were carried out to test the effect of drawing multiple drawpoints concurrently. These were:

- (i) isolated draw from a single drawpoint to measure the IEZ in both 1:30 and 1:100 scale models
- (ii) study of interaction of extraction envelopes:
 - (a) two drawpoints located at various spacings in a single drawbell. The length was set at 1100 mm, which corresponds to a separation distance between drawpoints of 15% with respect to the IEZ measured in the first test. This was done in the 1:30 scale model
 - (b) ten drawpoints. The simulation was carried out according to conditions at the Esmeralda block in El Teniente Mine in Chile. The separation between drawpoints was 1.15 times the width of the IEZ measured in the first test. This was done in the 1:100 scale model
- (iii) study of overlap of IEZs, which was done in the 1:30 scale model.
 - (a) Two adjacent drawpoints located in a single drawbell. The length was set at 500 and 700 mm respectively; the former

4 Widths of extraction zone as function of height of draw

referred at a 1 : 30 scale from that used at El Teniente 4 South Mine in Chile

- (b) study of overlap of IEZs from two adjacent drawbells. Geometry of these drawbells referred to that used at El Teniente 4 South Mine in Chile.

Isolated draw

In the 1 : 30 scale model, the maximum width of the IEZ was 800 mm for the full 3300 mm height of draw. If scaled at the geometrical scale used in the model those values would represent an IEZ width of 23.4 m at 100 m height. Figure 4 shows that the width of the extraction zone increases with the height of draw. The centroid of the extraction zone moves with the mass draw in the vertical plane across the drawbell. Initially the centroid was located at the drawpoint brow and moved to a final position located approximately 100 mm inside the drawbell. The final position of the centroid was reached when the IEZ was 1100 mm in height. In the section across the drawpoint the centroid is approximately at the centre of the drawpoint. Repeats of the same test were carried out and a standard error of 36 mm for the width of the IEZ was calculated.

5 Vertical view of extraction zones for different mass draw when two drawpoints were drawn interactively — 1100 mm long drawbell

In the 1 : 100 scale model, the draw was carried out until the IEZ reached 1400 mm (140 m scaled) high. This was achieved because with this model, the authors were able to simulate drawing in a real mine, in this case the Esmeralda block in El Teniente Mine, which has a block height of 140 m. However, the model was filled up to its maximum height, 3300 mm (330 m scaled). This was done to simulate the effect of overburden upon the geometry of extraction zones under concurrent draw, which matched the condition at the Esmeralda block in El Teniente Mine. There was an opinion within industry that the overburden might have an effect upon the geometry of extraction zones under concurrent draw, so this test and subsequent 10 drawpoints gave one an opportunity to test this opinion. There were three tests carried out in order to obtain the dispersion of the width of the IEZ. These tests produced the same maximum width, which was 420 mm.

Concurrent draw from two drawpoints in long drawbell

In order to test the limit of interaction between extraction zones, the drawbell was extended to a length of 1100 mm. This corresponds to an effective separation between centroids of extraction zones of 1.15 times the average maximum width of the IEZ at 3300 mm full height of draw respectively. Figure 5 shows the results of this experiment. The results are shown as a section looking across the drawbell. At the full height of draw the widths of the individual IEZs were found to be 785 mm on average. These are slightly less than achieved for isolated draw but within the range of the dispersion of results for a repeat of the same test that was carried out in previous work in the same model.¹⁰ It is clear therefore that at this drawpoint spacing there was no change in the shape of the extraction zones due to concurrent draw. The extraction zones of the two

6 Mid section of extraction zones in 10 drawpoints test

drawpoints therefore acted in a similar manner to the isolated extraction draw.

Concurrent draw from 10 drawpoints

As has been mentioned in the section on 'Isolated draw', this test was aimed to simulate draw for the Esmeralda block in El Teniente Mine. The separation between centroids of extraction zones was 480 mm, which corresponds to 1.15 times the maximum width of IEZ that was found in the isolated draw experiment at a draw height of 1400 mm. Figure 6 shows the plan view of the mid section of the extraction zones. It is obvious that there is no change in the shape of the extraction zones due to concurrent draw. As the model was filled up to 3300 mm, which means that the draw was carried out under overburden load upon the extraction zones, the indication is that the overburden does not have any effect upon the geometry of extraction zones under concurrent draw.

Concurrent draw from two drawpoints in short drawbell — geometry of combined extraction zones

As part of the experimental program the effect on the geometry of combined extraction zones was investigated when the spacing between drawpoints was less than the average width of the IEZ at the full height of draw. It was expected that the extraction zones of individual drawpoints would overlap. The effect of overlapping of extraction zones was investigated using two different drawbell lengths. As with the previous tests material was drawn concurrently. The first test was at 500 mm and the second at 700 mm drawbell length using the same material as before. In view of the offset of the IEZ

7 Extraction zones for each drawpoint, looking across drawbell — 700 mm long drawbell

centroid the extraction zones were at an effective distance of 300 and 500 mm respectively.

Figure 7 shows the development of the extraction zones as the material was drawn for the 700 mm drawbell. It can be seen that at up to a certain height of draw the extraction zones of both drawpoints were in isolation. Afterwards the individual extraction zones merged as they reached the IEZ width at which they would overlap. It is interesting to note that material immediately above each drawpoint was extracted by the closest exit point, meaning that lateral mixing did not occur when the drawpoints were drawn concurrently. The extraction zones for each drawpoint were separated by a well defined boundary, characterised by a vertical plane between drawpoints. The same pattern was confirmed by observations in the 500 mm drawbell experiment.

The height of the extraction zones reached the full height of the model faster in terms of mass than that in isolation. For the 500 mm drawbell an average of 1420 kg/drawpoint was drawn while for the 700 mm drawbell 1700 kg/drawpoint when the extraction zones reached 3300 mm in height. This is less when compared to the almost 2000 kg drawn to reach the same height for an isolated point of draw.

The geometry of the combined extraction zones was slightly different from that of the simply superimposing IEZ. Figure 8 shows a section passing through the

8 Plan view at mid height of draw with isolated extraction zones superimposed at the same height of draw — 500 and 700 mm drawbell lengths

1650 mm level in which the authors have plotted the extraction zones obtained in these experiments and the superimposed average IEZ geometry calculated from the isolated draw tests at the full height of draw. The combined extraction zones for the 500 mm drawbell tend to be slightly narrower in the direction along the drawbell (N–S in Fig. 8) and wider in the direction across the drawbell (E–W in Fig. 8). For the 700 mm drawbell experiment, the combined zones showed similar qualitative differences in the width but to a less extent.

The difference between the length of the extraction zone in the N–S direction and that derived from superimposing IEZs was less for the 700 mm drawbell when compared to the 500 mm drawbell. These results suggest that as the degree of overlap between adjacent extraction zones is increased, the shape of the combined extraction zone differs from that of superimposed IEZs.

Concurrent draw from four drawpoints with short minor apex

In this experiment, concurrent draw was carried out in four drawpoints located in two adjacent drawbells. The layout is a scaled down version of the one used in El Teniente 4 South Mine in Chile.¹³ In the physical model the scaled IEZ was found to be wider than the spacing between drawpoints. Therefore, it was expected that

9 Plan view at mid height of draw with each drawpoint extraction zone — four drawpoints in two 500 mm drawbells, 570 mm separation

overlap of IEZs would occur and all material between drawbells would be extracted.

In agreement with the results from the one drawbell experiment, material that was located immediately above the drawpoint was extracted by the nearest exit (see Fig. 9). In this experiment a total of 1100 kg was drawn from each individual drawpoint before the extraction zone reached the surface. This suggests that the amount of material drawn from a drawpoint will decrease as its extraction zone is overlapped by an increasing number of adjacent extraction zones.

Figure 10 shows the plan view at mid height of the combined extraction zones for the full height of draw. The average overlapping individual IEZ for the four drawpoints is superimposed over the combined actual extraction zone. It can be seen in Fig. 10 that the limit of the combined extraction zones for the four drawpoints drawn concurrently is smaller than the limit defined by simply superimposing the isolated extraction zone limits for each drawpoint. The effect of overlapping extraction zones is that the shape of the combined extraction zones is narrower than the shape defined by superimposing isolated extraction zones for each drawpoint.

In practice it is of interest to know the area of influence of the drawpoints in terms of extracted area. Table 1 shows a comparison between the actual extracted area and that calculated from superimposing IEZs. The calculations for the superimposed IEZ were based on the average IEZ width of 755 mm at half of its

10 Concurrent draw from four drawpoints in two 500 mm drawbells, 570 mm separation — plan view at mid height of draw with isolated drawzones superimposed

Table 1 Calculated and experimental extracted area

Experiment	Height IEZ, mm	Mass drawn/ drawpoint, Kg	Extracted area, mm ²	
			Calculated from overlapping average IEZs	Combined extraction zones
500 mm drawbell	3300	1450	666 952	694 000
700 mm drawbell	3300	1700	789 600	756 800
500 mm × 4 drawpoints	1500	300	548 000	548 000
	2100	500	817 600	714 400
	2700	800	1 042 800	886 400
	3300	1150	1 173 600	983 600

maximum height. The standard error for the area was calculated at 33·371 mm². From Table 1, it is observed that the area of influence was not different within the range of dispersion observed for the area, between the superimposed and combined extraction zones for the 500 and 700 mm drawbell length experiments. However, in the four drawpoints experiment there was a decrease in the area of the extraction zone that is significant at the 95% confidence interval. This difference in area was significant after enough overlap of extraction zones had occurred, in terms of the height that had reached 2100 mm after the IEZ.

Discussion and conclusions

There is currently debate within the literature with respect to the effect upon the extraction zone geometry of drawing multiple adjacent drawpoints interactively. One theory suggests that the area of influence of drawpoints can increase significantly with interactive draw if drawpoints are appropriately spaced relative to the isolated extraction zone geometry. Another suggests that the areas of influence remain unchanged with respect to isolated draw.

The largest 3D physical model constructed to study gravity flow in caving mines was used to study the effect of concurrent draw in a block caving geometry. To date a maximum of 10 drawpoints have been modelled. The indications to date are that horizontal extraction zone dimensions do not increase with interactive draw. Even when drawing under overburden load, there is no expansion of extraction zones.

In a previous publication,¹⁴ in which the authors investigated the interaction of movement zones and found no expansion of them under concurrent draw, it was suggested that current interactive draw theory appears to be largely derived from sand models. The use of a very low friction angle boundary condition that inhibits stress arching in the sand models may be the reason that this occurred. The media that was used in physical models discussed in this paper has a friction angle close to *in situ* caved material. Also, the shape of particles (angular) is more similar to *in situ* caved material than to sand (round). Therefore, it can be reasonably said that this physical model is significantly closer to *in situ* conditions when compared to sand models.

The extraction area, when the extraction zones overlapped, was smaller than would be obtained from overlapping isolated extraction zones. The width of extraction zones continued to increase up to the full height of draw. The centroids of the extraction zones were located 100 mm inside the drawbell. Those factors

could adversely contribute to the recovery of ore located over the major apex in the model.

In this paper, the actual values obtained in the model have been published without reference to scaled values. While there is evidence from full scale trials in sublevel caving mines that results from this large scale model could be scalable to the mine scale,^{10,14} it should be acknowledged that to date no full scale trials have been successfully completed in block caves.

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