

# 3D large scale physical modelling for studying interactive drawing and drawpoint spacing in Block Caving Mines

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## Abstract

*In block caving mines, the gravity flow of caved (broken) ore controls the amount of valuable material recovered and the extent to which it is diluted by caved waste rock. In addition, it also dictates the spacing, and thus the number of drawpoint required, which has a large impact on capital requirements for development of the mine. However, despite the large amount of research that has been carried out in the gravity flow field, 3D simulations of ore recovery and waste rock dilution can still not be done with confidence for conditions in a specific mine. Some mathematical models, in form of computer programs, have been developed. However these remain unvalidated due to the lack of validating data. It would be best to obtain this data from full scale tests. However experience has shown full scale tests to be very expensive, extremely time consuming and often the results from these tests have not yielded results that could be used effectively for the development of generally valid modelling approaches. Therefore, physical modelling remains as the only reliable way to do this task. It is the objective of this paper to describe the best method of physical modelling in order to produce reliable results which could be used to improve block caving mine design and validate mathematical models.*

# 1. INTRODUCTION

## 1.1. Background

Block Caving is a general term that refers to a mass mining method where the extraction of the ore depends largely on the action of gravity. By removing a thin horizontal layer at the mining level of the ore column, which is called undercutting, using standard mining methods, i.e. drill and blast, the vertical support of the ore column above is removed and the ore then caves as a result of the stresses induced around the undercut. As broken ore is removed from the mining level, the ore above continues to break and cave by gravity (Julin 1992). Eventually, the cave reaches the overlying waste or a surface boundary. Block caving is the lowest cost and most productive underground mining method, providing that all aspects are working well. One of the key aspects of a successful block cave is the control of dilution entry during the drawing of broken ore. The gravity flow of that broken ore controls the amount of valuable material recovered and the extent to which it is diluted by broken waste rock. The amount of ore recovered and waste rock extracted along with it has a huge impact on the economics of mining. In addition, the flow of broken rock also dictates the spacing, and thus, the number of drawpoints required, and the spacing of extraction level drives. The design of the extraction level has a large impact on capital requirements for development of the mine. This is particularly the case in large, low grade underground mining deposits that are seen by many mining companies as the future replacements for a significant percentage of current low cost large open cut mines. It is these large open cut mines that currently influence the profitability of many mining companies. Caving methods of mining such as block caving are widely regarded as the methods of choice for exploiting these deposits by underground methods in the future.

However, despite the large amount of research that has been carried out in the gravity flow field, 3D simulations of ore recovery and waste rock dilution can still not be done with confidence for conditions in a specific mine (Rustan 2000). As a result of our limited understanding of the mechanism controlling the flow, control of crucial dilution and ore recovery factors can be a difficult task. The key is to understanding flow in quantification of the influence of a large number of factors and their interrelationship.

In previous studies, a number of 2D and 3D mathematical models have been developed (Chen 1997; Gustafsson 1998, Alfaro and Saavedra 2004, Sharrock et al 2004) but these remain largely unvalidated. This was due to the lack of reliable validating data. The other problems in mathematical modelling are range and time. Itasca consulting group Inc. in the United States has developed a 3D numerical modelling approach for gravity flow of materials in the block caving mines based upon the particle flow code PFC3D. However, this package is currently limited to 20m block height due to the large number of particle needed. Moreover, the simulation of flow into one drawpoint to such height can take several days to execute on a fast computer.

All approaches to modelling flow of broken material in caving mining methods require good calibration and validation data. It would be best to obtain this data from full scale tests (Just et al. 1973; Rustan 2000). However experience has shown full scale tests to be very expensive,

extremely time consuming and often the results from these tests have not yielded results that could be used effectively for the development of generally valid modelling approaches (Gustafsson 1998; Just 1981; Sandstrom 1972). There is also a limited ability to change any of the critical parameters that are thought to influence flow of broken rock such as block height and draw point spacing, which limit the ability to quantify their effect.

The difficulties associated with full scale tests have resulted in the extensive use of physical models (eg Janelid and Kvapil 1966; Just and Free 1971; Kvapil 1965a; Marano 1980; Heslop and Laubscher 1981; Peters 1984). There are problems associated with the use of past physical modelling data to validate and calibrate mathematical models however. Gustafsson (1998) concluded that all shared at least one, and usually several, of the following limitations:

- Controlled, usually fairly narrow, size distribution.
- Two dimensional.
- No account of density differences generated by the blasting process.
- No refilling of the model from the top.
- Unrealistic frictional properties of walls.
- Insufficient markers in the model material.

Gustafsson therefore inferred that physical model tests carried out to date could not be reliably used to validate mathematical models for the prediction of flow characteristics of broken rock. In addition to those limitations, many of them only had single drawpoint, which is not suitable for block caving mines application.

Power (2004) used the largest 3D physical model ever constructed to study flow in an attempt to overcome the above limitations. However, he only modelled a single drawpoint. In block caving, the interaction of the drawzones of neighbouring drawpoints is considered to be the key to extraction level design and the control of dilution and ore loss. This work therefore aims to extend the physical modelling work carried out by Power to multiple drawpoints and interactive draw.

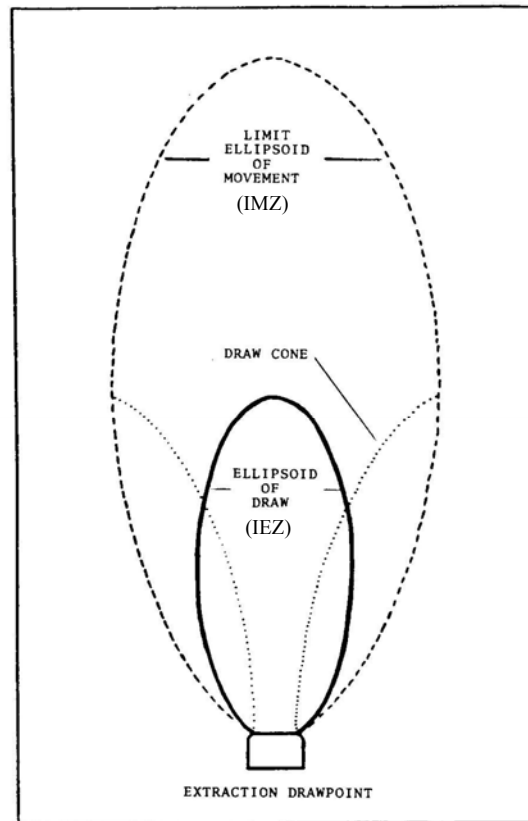
## **1.2. Terminology**

In the research of flow of broken rock in caving mines, there are two main concepts describing the shapes formed by material moving within the cave. Various authors have referred to these shapes in different ways.

The first of these is the outline or contour surrounding the original location of material that has been drawn from the drawpoint at any given point in time. This has been defined in various places as the ellipsoid of motion, the ellipsoid of draw, the ellipsoid of extraction, the draw body, the draw area, the draw envelope, or the draw zone. The author will retain the original term as used by each author in the literature review. However, for his own work, the author will use the term *Isolated Extraction Zone (IEZ)*.

The second concept is the outline or contour surrounding the original location of material that has moved from its original location (but not necessarily been removed at the drawpoint) at any given point in time. This has been called, amongst other things the limit ellipsoid, the loosening ellipsoid, the ellipsoid of movement, or the movement envelope. Again, the author

will retain the original term as used by each author in the literature review. However, for his own work, the term that will be used is *Isolated Movement Zone (IMZ)*. These concepts are shown in Figure 1.



**Figure 1. The draw and movement envelopes (Just 1981)**

The third concept is *interaction*. Interaction between two or more adjacent drawpoint extraction or movement zones is defined as when these zones expand from their isolated size under drawing process, as a result of drawing of neighbouring drawpoints. When these zones do not touch, they are defined as *isolated*.

## **2. Methods to simulate gravity flow of broken rock in caving mines**

### **2.1 Mathematical Models**

Mathematical models, in the form of computer programs, have been widely used as common engineering design tool. For example, numerical model programs such as MAP3D, FLAC3D and UDEC3D are currently common tools to predict stresses around underground openings. With the sophisticated computer technology available today, it is clear why mathematical models are often the preferred design tool for engineers.

In previous studies, a number of 2D and 3D mathematical models have been developed (eg Chen 1997; Gustafsson 1998; Alfaro and Saavedra 2004, Sharrock et al 2004) using a

stochastic or cellular automata approach, but these remains largely unvalidated. For example, Chen attempted to validate and calibrate his stochastic flow model with the results of physical modelling work carried out by Peters (1984). Peters' model was the largest physical model built to that time, in a frame approximately 4.5m high by 3.6m wide (Peters, 1984). However this model was essentially 2D (maximum experiment depth < 0.5m) and simulations were carried out using a very narrow range of particle sizes and distributions. Given that the physical properties of the broken material required by Chen's model were developed from this physical model, the use of the model to simulate the behaviour of broken material at a mine site is questionable. Nevertheless, Chen's stochastic model gave very good approximations to the results from the physical model. With modification, improved validation and calibration data, Chen's model has great promise as it is computationally efficient. Gustafsson attempted to use data from full scale experiments to validate and calibrate his stochastic model. However, the results of these experiments were largely inconclusive. The use of his model in its current form to predict gravity flow of material in at a specific site must therefore also be questioned. Gustafsson's full scale test will be described in the next sub-section. Sharrock et al (2004) developed CAVE-SIM, which is based on cellular automata approach. This package has been validated with results from Kvapil's sand model experiments (Kvapil 1965a, Janelid and Kvapil 1966). However, as will be described later in this paper, sand models have some drawbacks which make this model not suitable to simulate gravity flow of broken rock, such as inability to measure extraction zone, particle size, particle shape, and friction angle.

Cundall (Trueman 2004) has begun the development of a 3D numerical modelling approach for gravity flow of materials in the block caving mining method based upon the particle flow code PFC3D. This approach has a possible advantage over the stochastic models in that it attempts to model the physical process of rock interaction. However, the physical process as modelled by PFC3D remains largely unvalidated because of the lack of reliable data from either physical models or full scale tests. Trends and results from the model that contradict current thinking can therefore be challenged. Also, the application of 3D particle flow codes is currently limited to very few drawpoints and extraction heights due to the large number of particle needed. Even the simulation of flow into one drawpoint to a height of extraction of 20m can take several days to execute on a fast computer. Modern block caving extraction heights vary between 140 and 500m. Inclusion of more realistic heights of extraction will further extend computation times.

Another numerical package that has been developed is REBOP (Rapid Emulator Based on PFC3D) (Carlson et al 2004, Pierce 2004). This model is a response to the difficulties associated with run times in particle flow codes. This model encodes algorithms that describe collapse and erosion during drawing. The input parameters into the algorithms describing erosion and collapse are empirically derived. It was envisaged that PFC3D would be used to produce the necessary empirical data. However, due to the fact that PFC3D cannot practically model sufficient height of draw or number of drawpoints and concerns relating to the modelling of surface roughness, this is not now the case. The empirical data is being derived from the results of the physical model derived both during this study and those of Power (2004). The quantitative understanding of the mechanics of gravity flow being developed as part of this thesis is therefore essential for the development of REBOP.

Other theoretical approaches to the study of the flow in granular materials have idealized it as a continuum (eg Haff 1983; Savage and Hutter 1989; Hwang and Hutter 1995, Verdugo and Ubilla 2004). However, the applicability of using a continuum approach to model granular flow remains debatable. However, the applicability of using a continuum approach to model granular flow remains debatable. The former three assumed granular materials as a fluid. However, the particles in granular materials are not uniform in size and shape, whereas in fluid, the molecules size and shape are uniform, i.e. spherical. This causes significant difference in contact between particles or molecules thus influences stress distribution throughout the media. Kvapil (1965b) stated that pressure transmission in granular materials may take many forms because the grouping of the particles may be random and variegated. This means that Pascal's law, which states that pressure in a fluid is distributed uniformly to all direction, may not be valid in granular materials.

Verdugo and Ubilla (2004) suggested that since the drawing process of caved rock in a drawpoint is non continuous and only take 6 to 8 tonnes of material, the flow of caved rock are slow and inertial forces acting on it is small and can be neglected. Thus the whole phenomenon can be considered static and differential equations for static equilibrium of a continuum media are valid. However, Janssen (Hustrulid and Krauland 2004) found that the full weight of granular materials in a bin is not carried on the bottom of the bin, as the case of solid (continuum) materials. Some of it is transferred as horizontal pressures. This means that the stress distribution in granular materials is different than the one in solid materials.

Nevertheless, when properly validated, mathematical models can be a powerful tool to simulate gravity flow. However, the work of providing reliable validating data must be carried out beforehand. It is then necessary to review the full scale test and physical modelling for this purpose.

## **2.2 Full scale Tests**

Only five extensive full scale tests to study the flow of granular material in caving mining have been reported in the literature, all for sublevel caving (SLC) mines rather than block caving Grangesberg, Sweden (Janelid 1972), He-Pei, China (Chen and Boshkov 1981, Rustan 2000), Kiruna, Sweden (Gustafsson 1998; Quinteiro et al 2001), Ridgeway, Australia (Power 2004), and Perseverance, Australia (Hollins and Tucker 2004). The principle behind these tests was placing individually identifiable markers within experimental production rings in internal fans of marker rings. The coordinates of each marker (X, Y, Z) were recorded and from markers recovered at certain tonnage drawn, extend of the drawzone could be plotted at that point.

All full scale tests were carried out for specific geometries and the application of the results to a generalized idealization of flow in block caving mines is not possible. Full scale tests have never been carried out for a block caving mine undoubtedly because of the considerable increased cost and difficulty in achieving this relative to an SLC mine for the following reasons:

- In current block caving mines, the block or the draw height is more than 150m, which is far beyond the range of available drill machines. Placing markers up to significant block height will be difficult and very expensive.
- Assuming that markers could be placed along the block height, it will take years to complete one test. In sublevel caving, one blasted ring is mucked completely within days, whereas in block caving, one drawpoint is drawn for years. Also, recovering the markers will be a major issue since with such large geometry, the amount of markers that must be placed will be very large.
- It is likely that movement of markers will be influenced not only by flow, but also by the caving process.
- The cost of such a test will be magnitudes greater than for an SLC geometry. The full scale tests carried out by Power cost approximately \$25,000 for a test carried out per blasted ring (Power 2004). The size of the ring was 14m wide, 37m high and 2.6m deep. In a block caving geometry, where the draw column is typically 18m wide, 15m deep and more than 150m high, the cost will be millions of dollars. Moreover, due to interactive environment of the drawing, it has been suggested that the test must be carried out in 9 drawpoints, which will make the cost much more expensive.

Alvial (1992) did attempt a partial full scale test in a block caving geometry. He put markers (old tyres) in the extraction level of a mined out sector above Teniente 4 South sector in El Teniente mine, Chile. Within 10 years, 19 markers were recovered in the drawpoints. Since it was only single layer of markers, the markers generally provided only slip information and marker trajectory. No even site specific flow rules could be developed from the results of the test.

Even if a successful full scale test could be achieved in a block caving environment, results will be insufficient to develop generalized rules because critical parameters such as fragmentation size, drawpoint spacing and block height can not be varied. Multiple successful full scale trials in different block caving geometries will be required. The likelihood of achieving this in the foreseeable future is remote. Nevertheless, even limited full scale tests will improve the confidence that we have in model results.

### **2.3 Physical Models**

The use of physical model in caving mines has been carried out for almost a century. Lehman (1916) and McNicholas et al (1946) used physical model to study the ore recovery in Miami copper mine and Climax Molybdenum mine in the United States. They used crusher ore and waste as the material. The drawn material was sampled and assayed, and this was used to assess modelling results. They carried out experiments by varying the ore and waste fragmentation, and chutes (drawpoint) spacing. However, they only produced qualitative results, i.e. the effect of chute (drawpoint) spacing to the ore recovery. Since no markers were placed in the model, they did not make any measurements of the drawzones. However, McNicholas observed that coarse fragmentation yielded larger arches than fine one, thus concluding that coarser material could be drawn at wider drawpoint spacing than the finer one.

To date, there have been two kinds of physical model based on the material used: sand and gravel models. Early physical modellers used sand as the material due to the easiness in handling and the reduced overall scale of the model. From these models, concepts of gravity flow of broken material in caving mines were initiated, many of which are still used.

### 2.3.1. Sand models

Kvapil (1965a, 1992) appeared to be the first person to attempt a quantitative approach for the gravity flow of broken rock. His first work aimed to provide mathematical relationships relating to the flow of granular material in hopper and bins. Shortly afterwards with Janelid (Janelid and Kvapil 1966) he extended this work into idealizing gravity flow for large scale iron ore mines in Sweden which used sublevel caving as their mining method. Although just using small scale 2D models initially, his work proved to be significant and was used as a design tool for many years.

Kvapil constructed a simple vertical glass model (bin) with layered white and black sand filling. The model had a slot in its bottom. When the slot was opened, the sand flowed out in phases shown in Figure 2. It can be seen that only a certain part of the whole material in the bin started moving at the time the slot was opened.

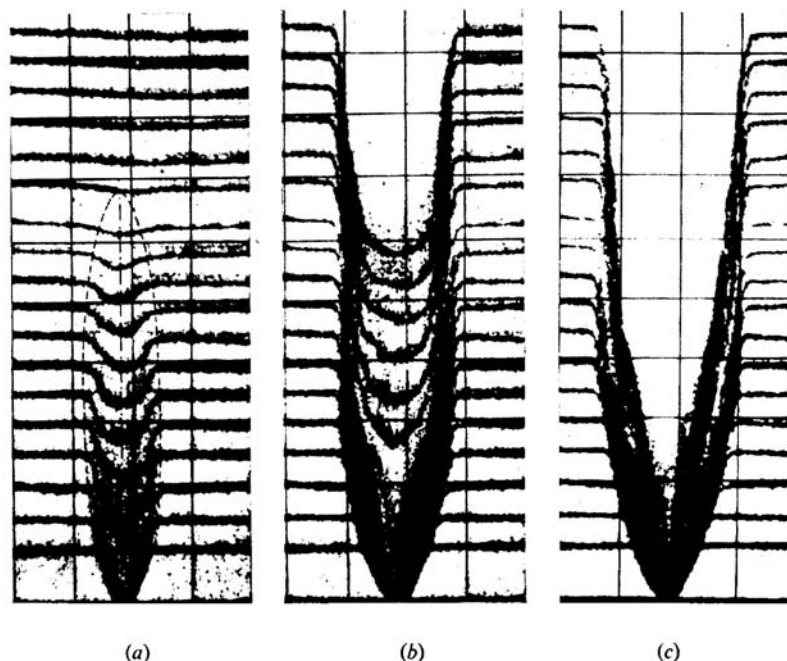


Figure 2. Kvapil's model (Kvapil 1965a)

Based on observation in this model, it was postulated that the material that had been discharged after a given period of time was originated from within an approximately ellipsoidal zone which Janelid and Kvapil (1966) termed the ellipsoid of motion, draw or extraction. Beside it, there is another zone which they termed the limit or loosening ellipsoid.



Material between the ellipsoid of motion and a corresponding limit ellipsoid was loosened and displaced but did not reach the discharge point (the slot). The material outside the limit ellipsoid remained stationary. As draw proceeded, an originally horizontal line drawn through the material deflected downwards in the shape of an inverted cone. The shape of this draw cone indicated how the largest displacements occur in a central flow channel. This theory is shown in Figure 3.

The shape of a given ellipsoid of motion can be described by its eccentricity

$$\varepsilon = \frac{1}{a_N} (a_N^2 - b_N^2)^{1/2}$$

where  $a_N$  and  $b_N$  are the major and minor semi-axes of the ellipsoid of motion as shown in Figure 3. The ellipsoid shape and size is determined by particle size of the flowing material at the same discharge opening width and the height to which the material is drawn. Small particles were found to have greater eccentricity than the larger ones, and thus had a slimmer and more elongated shape. The eccentricity increases with increased draw height.

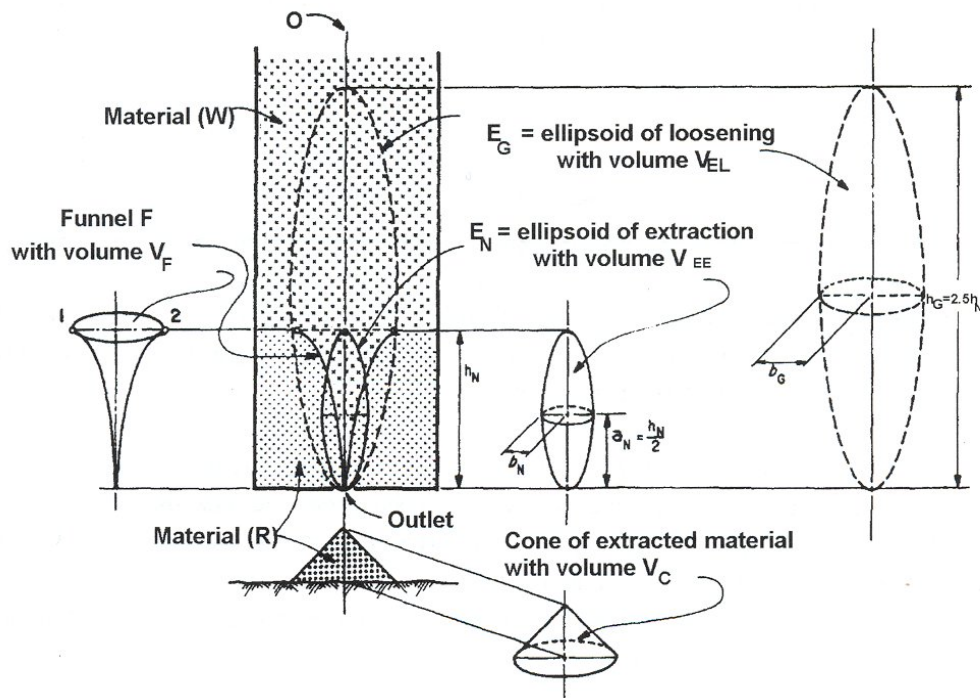
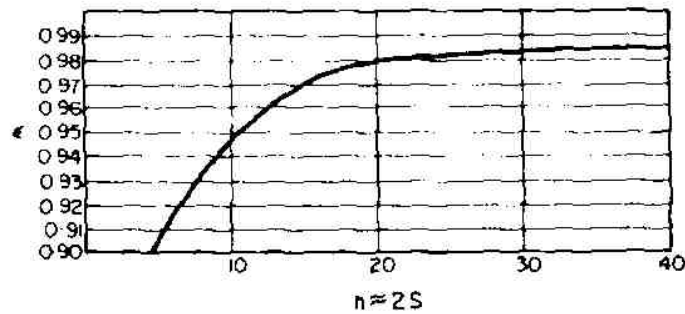


Figure 3. The ellipsoid theory (Kvapil 1992)

It was assumed that the horizontal cross section of the ellipsoid is circular. In practice,  $\varepsilon$  varies between 0.90 and 0.98 depending on the draw height as shown in Figure 4. It is considered that the range of 0.92 to 0.96 being most common, at least for SLC mines.



**Figure 4. Eccentricity values (Janelid and Kvapil 1966)**

With the larger draw heights in block caving, eccentricities greater than 0.96 may be more appropriate even though fragmentation tends to be coarser than in SLC mines. Since  $a_N$  is half the draw height,  $b_N$  then could be calculated using the equation above. Janelid and Kvapil thus developed the design criteria of sublevel caving mines based on this ellipsoid concept, such as location of sublevel drifts, ring burden, and the optimum width of the drawpoint drift relative to the fragmentation size of the broken ore.

There is another method to calculate  $b_N$  (Janelid and Kvapil 1966). If the volume of discharged material,  $V_N$ , and ellipsoid height,  $h_N$  is known, then  $b_N$  could be calculated using equation:

$$b_N = \sqrt{\left(\frac{V_N}{2.094h_N}\right)}$$

Regarding the limit ellipsoid, Janelid and Kvapil provided relationships as follows. It was assumed that the limit ellipsoid has the same shape, thus eccentricity, with the ellipsoid of motion. The material between two ellipsoids will loosen and displace but will not report to the discharge point. This loosening is described by the loosening factor  $\alpha$  as

$$\alpha = \frac{E_G}{E_G - E_N}$$

where  $E_G$  is the volume of the limit ellipsoid and  $E_N$  is the volume of the ellipsoid of motion. The value of  $\alpha$  varies from 1.066 to 1.100. Janelid and Kvapil stated that in most granular materials,  $\alpha$  tends towards the lower figure of 1.066. If we apply this figure to equation above, we obtain

$$E_G \approx 15E_N$$

This means that the volume of the limit ellipsoid is about 15 times greater than the volume of the ellipsoid of motion. Thus the height of limit ellipsoid  $h_G$  could be approximated as

$$h_G \approx 2.5h_N$$

Kvapil's ellipsoid theory since then has been widely accepted as a design guideline in sublevel caving mines around the world. However, some subsequent sand modellers found that this theory does not model the flow accurately (Heslop 1983; Heslop and Laubscher 1981;

Laubscher 1994, 2000; Marano 1980; McCormick 1968). McCormick found that the shape of the body of motion resembles a cylinder with cone shape at the base. Marano, Heslop and Laubscher (1980, 1981, 1983, 1994, 2000) also observed a similar thing in their sand model. Their model will be discussed in detail later in this sub-section.

The author made comparison between the values of  $b_N$  calculated using the chart shown in Figure 4 and the result of the 3D large scale gravel model experiments carried out by Power (2004) and JKMRC (2003) as shown in Table 1. The gravel models will be discussed in the next section.

**Table 1. Comparison between  $b_N$  obtained from ellipsoid theory and 3D large scale gravel model**

Case	$h_N$ (m)	$a_N$ (m)	$\epsilon$	$b_N$ (m)	$b_N$ from gravel model (m)
Modern Kiruna	47.5	23.75	0.988	3.7	6
Ridgeway	37	18.5	0.983	3.4	5.4
Block cave IEZ (P <sub>50</sub> 5mm)	102	51	0.99	7.2	9
Block cave IEZ (P <sub>50</sub> 20mm)	102	51	0.99	7.2	13.5

A comparison was also made with the results of the full scale test carried out at He-Pei mine in China (Chen and Boshkov 1981, Rustan 2000) as shown in Table 2. This full scale test will be described in detail in Section 2.3.3.

**Table 2. Comparison between  $b_N$  obtained from ellipsoid theory and He-Pei mine full scale test**

$h_N$ (m)	$a_N$ (m)	$\epsilon$	$b_N$ (m)	$b_N$ from full scale test (m)
18	9	0.977	1.9	3.0
27	13.5	0.980	2.7	5.0
34	17	0.982	3.2	6.1

The discrepancies between values obtained from ellipsoid theory with the gravel model and full scale test suggest that the sand model is not suitable to simulate gravity flow in caving mines.

In spite of that, many mining textbooks today still contain this theory (eg Brady and Brown 1993; Brown 2002; Hartman 1987). This demonstrates the general acceptance of the ellipsoid theory.

It is interesting to note that since Kvapil published his ellipsoid theory, no one ever tried to apply this theory to block caving mines until the 1980's. Kvapil himself carried out some experiments in multiple discharge openings hoppers (Kvapil 1965a). He concluded that to

ensure good hopper activity, the distance between openings should be less or equal than the width of mobile flow, or the width of the ellipsoid of motion. With this arrangement, the formation of passive zones between openings will be limited to a minimum. However, no one carried out further research in this area until Marano, Heslop and Laubscher did it in early 1980's.

In the late 1980's when working as a consultant at El Teniente mine, Kvapil extended his ellipsoid theory to determine drawpoint spacing (Flores 1993, 2004). He proposed an equation to calculate the spacing (S):

$$S = 2b_N + w_a$$

$w_a$  is the effective drawpoint width, i.e. the loading width of broken ore in the drawpoint. It was assumed that  $w_a$  is approximately 75% the drawpoint width (Flores 1993). From this equation, it is clear that the spacing should be at least equal to the width of the ellipsoid of motion.

This theory was challenged by Laubscher, Heslop and Marano (Heslop 1983; Heslop and Laubscher 1981; Laubscher 1994, 2000; Marano 1980). They carried out experiments in a 3D sand model, which was specifically built to investigate the interactive drawing of adjacent drawpoints. The model consisted of a metal box with a size of 760mm long x 760mm wide x 2400mm high. The base contained 50 holes, evenly spaced, with a diameter of 25mm, representing the drawpoints. The spacing between each hole was 108mm, but could be varied for different experimental conditions by closing some of the drawpoints. In order to simulate the actual condition in mines, a modelled crown (major apex) pillar, made of polystyrene foam, was placed above the drawpoints.

The scale of the model was 1:80. This represented the ore block of 60m long x 60m wide, with 2m drawpoint width. The block height could be varied by filling the model to the top or only part of it. When full to the top, it would simulate a block height of 192m at the scale used. The material used was mostly river sand, with median size ( $P_{50}$ ) of 0.7mm. In some experiments, the river sand was mixed with pit sand, creating a median size of 0.6mm. When scaled up, this represented mean ore fragmentation sizes of 56mm and 48mm respectively, which would represent a very fine caved insitu fragmentation. However, the friction angle of the material was less than caved insitu material ( $34^\circ$  vs  $45^\circ$ ). Drawpoints in this model were drawn simultaneously

To monitor the movement of the material under draw, coloured layers of sand were used. This was done by mixing the river sand with a powder pigment and adding a little cement to fix the colour of the sand. The coloured horizontal layers were placed at regular intervals in the sand. A total of six layers were used, spaced 150mm apart and 30mm thick each. At completion of the experiments, water was poured on top of the sand in the model, in order to wet it thoroughly. When watering, all drawpoints were closed using ordinary masking tape, to avoid any loss of sand. Draining the water was allowed by making small holes in the masking tape. It was found that the wet sand had enough cohesion to permit the cutting of vertical sections through the material and allowing the observation of the position of the coloured layers by means of detailed sketches, as shown in Figure 5, 6 and 8. It was claimed that a high degree of

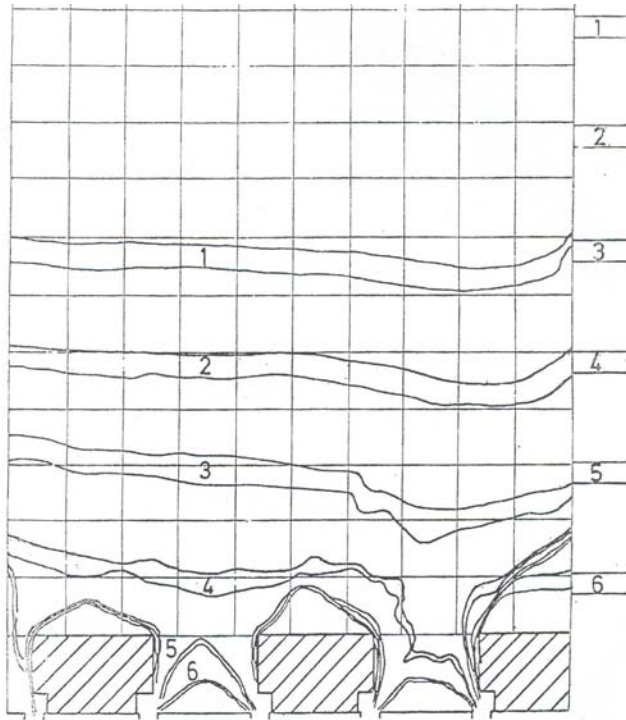
accuracy was obtained. Also the watering technique was claimed to be very practical and work very well. Some compaction was observed, resulting in a small overall lowering of the layers, but this was considered negligible.

Laubscher, Heslop and Marano (1980, 1981, 1983, 1994, 2000) carried out experiment in which the drawpoints were spaced at the width of the isolated drawzone (IDZ), which was measured to be 108mm from previous experiment. They found that uniform lowering of the upper markers occurred when the drawpoints were drawn simultaneously as shown in Figure 5. They then compared this result with the reconstructed drawzone of isolated drawpoint experiment carried out previously at the same drawpoint spacing as shown in Figure 6. From this comparison they then concluded that the ellipsoid theory does not apply in this situation, which later they termed as *interactive flow theory*.

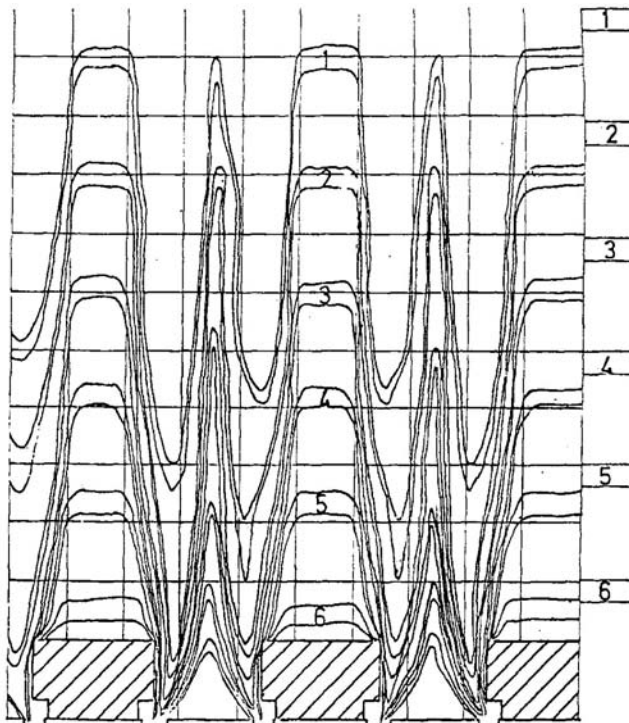
From this experiment, Laubscher then proposed his drawpoint interaction theory. He stated that based on the model experiments and interpretation of stresses around underground excavations, interaction will occur when the drawpoints are spaced at 1.5 times the width of the isolated drawzone (Laubscher 1994, 2000). This means that the IDZs are widening. The mechanism behind this widening was described as failure of the pillar of broken material between IDZs. This failure is caused by the increasing of vertical stress and decreasing of lateral stress within the pillar, which then induced lateral movement of broken material within the pillar. Both vertical and lateral stresses were measured in the model using load cells. He also stated that this result has been confirmed by observation of the fine material extracted in the mines and by the behaviour of material in bins. This mechanism produces an even rate of subsidence, or “mass flow”, or uniform draw down as shown in Figure 7. This theory has been widely accepted and used in many block caving mines.

This concept, however, has some questions. Firstly, Laubscher never made any detailed explanation about how he made this conclusion based on the model experiments. He also never explained how he confirmed this by observation of the fine material extracted in the mines and by the behaviour of material in bins. He did carry out an experiment in which the drawpoint was spaced at 1.4 times the width of IDZ, as shown in Figure 8. However, there is no uniform drawdown in this experiment, although the material between drawpoints, or the “pillar” as Laubscher termed it, was lowered from its original position.

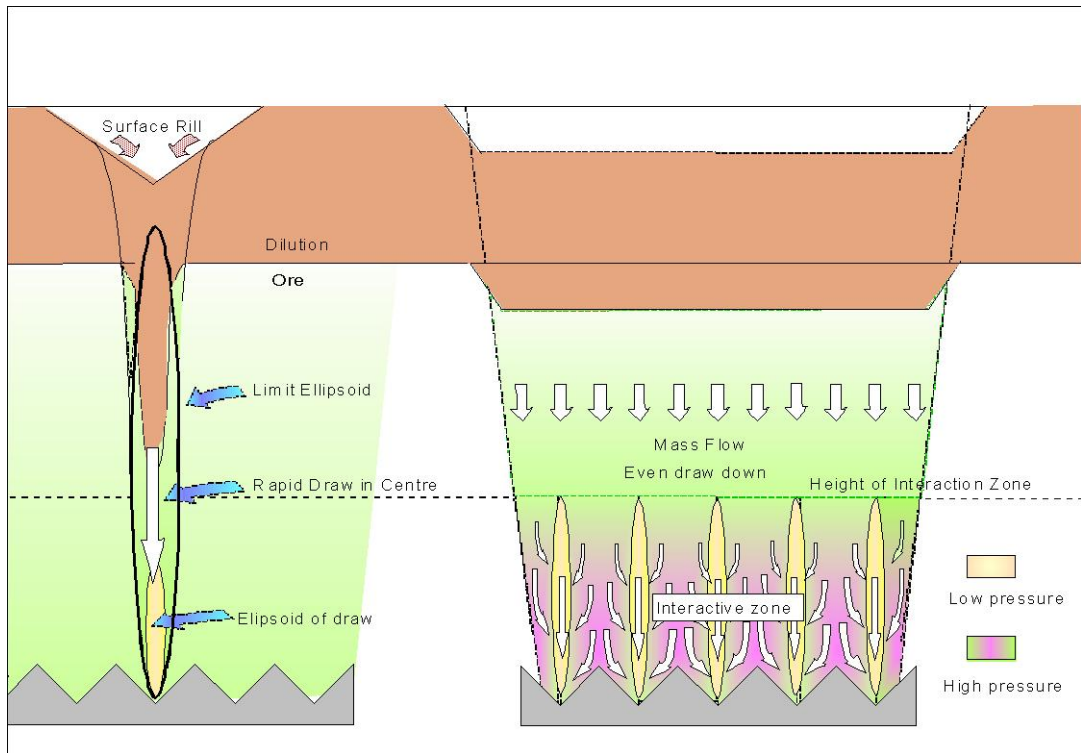
Secondly, Laubscher, and also Heslop and Marano as well, appeared to fail to recognize that the term “isolated drawzone” they used referred to the zone of movement or ellipsoid of loosening in Kvapil’s ellipsoid theory. It is obvious from Figure 6 that the 108mm wide drawzone as referred by Laubscher, Heslop and Marano is the width of the glory hole, and that glory hole is obviously the movement zone, since the upper layer of coloured sand did not reach the drawpoint.



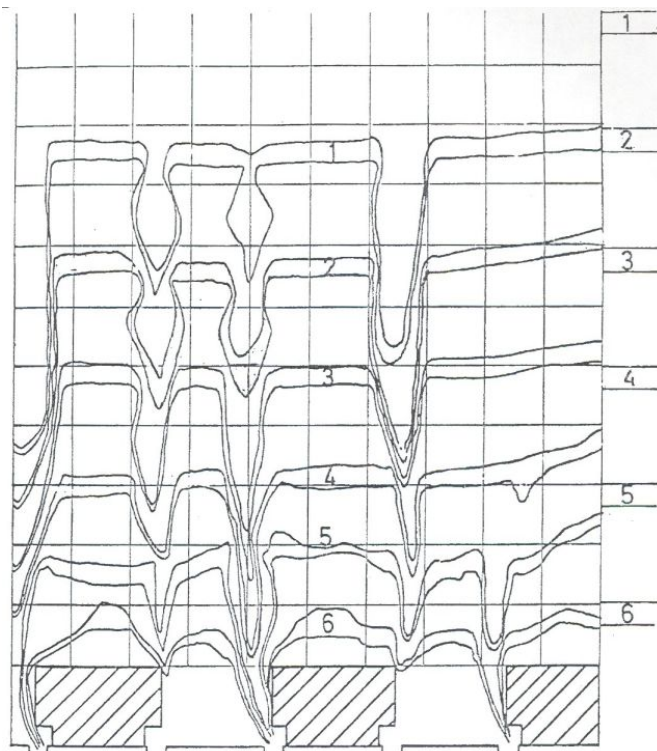
**Figure 5. Draw pattern at drawpoint spacing equal to the drawzone width (Heslop 1983)**



**Figure 6. Reconstructed draw pattern of isolated drawzones at spacing equal to drawzone width (Heslop 1983)**



**Figure 7. Laubscher's interactive flow theory (Laubscher 2000)**



**Figure 8. Draw pattern at drawpoint spacing 1.4x the drawzone width (Heslop 1983)**

It is clear that a major drawback in sand models is measuring the zone of extracted material accurately. It is impossible to place any individual recoverable markers in the model so that only the movement and not the extraction zone can be accurately determined.

Another possible drawback of using sand models is the shape of particles. Rounded particles such as sand will have greater mobility than the angular particles which are characteristic of caved ore (Richardson 1981). The friction angle also has an effect on the draw width (Janelid 1972). The friction angle of sand will also tend to be lower than caved ore (or gravel) and a greater friction angle will tend to increase the draw width for a given draw height. Also, the size of sand particles when scaled up does not resemble the fragmentation of current block caving mines, which can have very coarse caved ore.

### **2.3.2. Gravel models**

Gravel models offer closer resemblance with caved ore in the mines. However, as the particle size increases significantly, the model is also much larger than the sand models for similar scales. As a result, the models that have been built had very large scale, such as 1:20 in Janelid's model (Janelid 1972) and 1:30 in Power's model (Power 2004).

Janelid (1972) carried out experiments in 3D at a scale of 1:20 of the Grangesberg SLC mine in Sweden. The aim of this work was to investigate the scaling factor from the model scale to full scale. Janelid's full scale test has been described in Section 2.2. The model simulates the full scale test area in Grangesberg mine. The gravel was derived from crushed ore from Grangesberg mine. Markers were placed in horizontal layers to define the zone of drawn material. However, since the model was built specifically for that mine, no general rules for the flow of granular material could be deduced from the results. A primary outcome from this work was a comparison between full scale test and large scale model results. It was found that both results were similar, although the model result was slightly narrower. Janelid commented that this was due to the less packed and more movable material in the model. Based on this result, Power (2004) concluded that a large scale model can give similar result to the full scale one, and this formed a basis for his 3D model which will be discussed later in this sub-section. The similitude of the model and the full scale will be discussed in Section 2.4.

Peters (1984) built the largest physical model ever created to at that time. The model dimension was 4.5m high, 3.6m long but less than 0.5m wide, which essentially made the model two-dimensional. The aim of his work was to investigate the effect of particle size and drawpoint width on the size and shape of the zone of drawn material in single drawpoint tests and the effect of varying drawpoint spacing in multiple drawpoint tests. A big departure from many previous physical modellers was that he used broken rock as the model material, sized at 0.5, 1.0, and 1.5in respectively and also the 1:1:1 mixture of these sizes. Markers were placed in horizontal layer inside the model to define the zone of drawn material, which he termed the draw envelope. The results of his single drawpoint tests are shown in Table 3. From this table, it is clear that the width of the draw envelope is not affected by the particle size. This finding contradicted Kvapil's ellipsoid theory. Power (2004) carried out tests in a 3D gravel model and also found particle size effect on the width of the draw envelope, concluding that the two-dimensional nature of Peters' model is one major factor contributing to this finding, since the



growth of the draw envelope is constrained in one dimension. Power's model will be discussed later in this sub-section.

In his multiple drawpoint tests, Peters found that no interaction occurred when the drawpoint was spaced at two times the width of isolated draw envelope. However, when the spacing reduced to factor of 1.14, interaction occurred. This again contradicted Kvapil's theory, but appeared to give some support for Laubscher's interaction theory (see Section 2.3.1). However, Peters only carried out one test, and a 14% change in the width of draw is within the variation of identical tests repeated as found by Power (2004). It was also possible that the 2D nature of his model caused this interaction. Peters said that this growth occurred as a result of interaction of the movement envelopes of two drawpoints, which made the material between drawpoints become looser and easier to move.

**Table 3. Results of Peters' model (Peters 1984)**

Rock size <sup>1)</sup> (in)	Drawpoint width (in)	Measured width of draw <sup>2)</sup> (ft)
0.5	4	2.50
0.5	8	3.60
0.5	12	3.60
1.0	4	2.80
1.0	8	3.00
1.0	12	3.50
1.5	4	2.83
1.5	8	3.55
1.5	12	3.50
1:1:1	4	2.50
1:1:1	8	3.60
1:1:1	12	3.60

<sup>1)</sup> These numbers are nominal size from three size groups: 0.25-0.75in, 0.75-1.25in, and 1.25-1.75in respectively.

<sup>2)</sup> This is the widest section of the draw envelope

Although Peters' model was large scale and used gravel as the model media, Power (2004) questioned the validity of the results relative to mine scale because of the 2D nature of the model and 3D nature of the full scale. This was the main factor behind the work carried out by Power to build a large scale 3D gravel model. Power's model is the largest model ever built to date, with dimension of 2.2m long x 2.1m wide x 3.3m high. The scale of the model was 1:30. The tests carried out in this model were similar to those carried out by Peters but in 3D rather than 2D. Power carried out experiments with gravel in a narrow size distribution and median particle sizes of 5mm, 7mm, 14mm, 20mm and a very wide size distribution mixture of fine and coarse particles with a median size of 14mm. As did Peters, Power also placed markers to define the extent of the draw envelope. Since the model was 3D, the markers density was greater than in Peters' model. The major outcome of Power's work was particle size effect on the width of the drawzone, as shown in Figure 9. The results clearly showed that particle size does effects draw width thus agreeing with Kvapil's original conclusions and contradicting the

conclusions made by Peters. Power then concluded that the difference between his and Peters' results was clearly due to the 2D nature of Peters' model.

It is interesting to note that particle sizes of 14 and 20mm have similar width of draw envelope. These particles when scaled represent the typical caved ore fragmentation in current block caving mines. Power stated that the reason for this is uncertain and he suggested that it would be interesting to conduct experiments with particle sizes greater than 20mm. However, due to the size of the drawpoint in his model, this was difficult due to fact that hang-ups would become a problem. Nevertheless, Power's model results demonstrated that coarse particles will yield wider draw area than fine ones.

Power's model only had one drawpoint and thus he only carried out experiments of isolated draw. The effect of drawing adjacent drawpoints interactively was not carried out. This is not suitable for block caving mines simulation since interaction between adjacent drawpoints is the one that matters. Therefore, a multiple drawpoint model must be used.

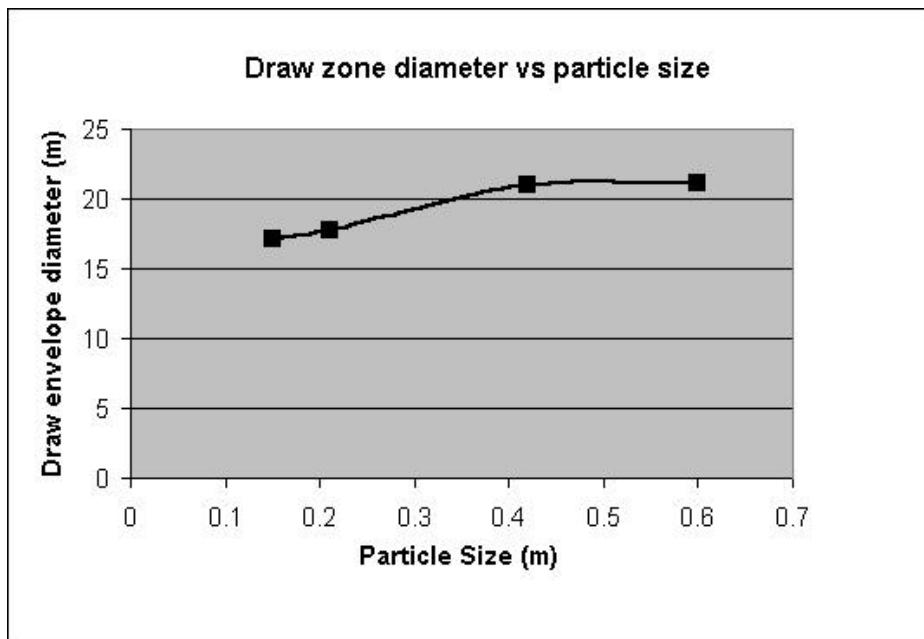


Figure 9. Results of Power's model (Power 2004)

### 2.3.3. Similitude

To guarantee that the results of a physical model can be directly scaled up, the model must be fully similar to the mine scale. A physical model of a caving mine that satisfies all forms of similitude is thought by most workers in the field to be impossible to construct (eg Peters 1984; Rustan 1990). It is important to note that the similitude achieved in all physical models that have been built is only geometrical similitude, i.e. the length scale. This is understandable, since this similitude is the easiest to achieve. However, Mandel (1963) stated that tests on reduced scale models are based on the possibility of changing the three scales of length, time

and force (mass) without thereby altering the equations describing a mechanics phenomenon. Therefore dynamic similitude must also be achieved to achieve full similitude.

Dynamic similitude refers to the scaling of forces within the model. This is almost impossible to achieve, since all of the forces in place in caving mines (e.g. compaction, horizontal and vertical stresses) cannot be represented in the physical model (Power 2004). Sandstrom (1972) stated that since the mass of geometrically scale particle would be divisible by the cube root of its scaling factor, the forces on the scaled particle will be much too small. The author so far cannot find any evidence that any of the physical models that have been built have achieved dynamic similitude.

However, Power (2004) concluded that there was evidence to suggest that if the scale of the physical model was large enough, giving 1:30 or better as a general guideline, then the lack of dynamic similitude would not significantly impact upon the main focus of flow research, the width of the draw envelope within the model. Power therefore concluded that 3D large scaled, geometrically similar physical models can give a representative indication of full scale conditions, using the work of Janelid (1972) and comparison between his full scale tests and physical model results.

Janelid compared the results of extensive full scale tests at Grangesberg mine in Sweden against 3D physical modelling work carried out an exact replica of the mine, at a scale of 1:20 (Janelid 1972). Janelid's full scale test and model has been described in Section 2.2 and 2.3.2. Janelid's comparison showed that breadth and depth of flow in the model were almost identical to that measured in full scale. Janelid found that the height of draw was identical in model and full scale up to 60% draw, after which drawbody growth rates in the full scale tests were less than in the model experiments, with a difference of 16% at 120% draw. Janelid concluded that the coarser material at the top of the fired rings did not flow as easily as the homogenous model media. Power (2004) also compared the physical model results obtained by JKMRC (2003) at a scale of 1:30 with the width of draw obtained from his full scale tests at the Ridgeway SLC mine, thus concluding that the model results were directly scalable. The depth of the draw zone could not be directly scaled but this was considered to be a result of incomplete breakage of the full burden at the mine scale, which he considered maybe endemic to modern SLC geometries. Blasting issues are not a consideration in block caving mines.

The author compared that JKMRC physical model results with the full scale test done at He-Pei magnetite mine in China (Chen and Boshkov 1981, Rustan 2000). Unlike Power's full scale test, they managed to break the full burden since they used 8 blast rings with 1m burden on each ring, and they created a vertical slot in front of the ring prior to firing. This caused the blasted ring became free flowing material, which is similar with the physical model. This is why this test is a good comparator to the physical model results. The depth of both model and full scale test are very similar. For example at 50m draw height, the depth obtained in the model was 6.9m (scaled) whereas the full scale test showed 7.2m.

Nielsen and Askegaard (1977) concluded that the volume forces in a model could be neglected if the tests in the model were carried out with a non cohesive media and the model size is not

too small. This conclusion came from their experiments with a centrifuge to investigate scale errors in modelling the flow of granular material in silos.

Nevertheless, it has been found that at least one parameter of dynamic similitude in caving model, the draw rate, can be scaled down (Castro 2003), as described below:

The draw rate is expressed as tons/day. Therefore, there are two parameters that have to be scaled down: mass and time, as noted below:

#### 1. Mass

Mass is the product of the density and volume, expressed as:

$$m = \rho V = \rho L^3$$

If we scale the L by a factor k, therefore:

$$m' = \rho' (kL)^3$$

If the rock type in the model and in the mine is same, we can assume that the density is same. Thus  $\rho = \rho'$ , therefore

$$\frac{m}{L^3} = \frac{m'}{(kL)^3}$$

$$m' = k^3 m$$

The mass scale factor is  $k^3$ .

#### 2. Time

It is necessary to ensure that the particle accelerations in the model were similar to those in the full scale situation. The rule for scaling the accelerations is simple. Assume that a rock fragment in the full scale (the mine) suffers a unit acceleration moving a distance  $l$  in a characteristic time  $t$ . Since the acceleration is given by

$$a = \frac{l}{t^2}$$

The acceleration should be the same in each case, so

$$a_{\text{mine}} = a_{\text{model}}$$

$$\frac{l_{\text{mine}}}{t_{\text{mine}}^2} = \frac{l_{\text{model}}}{t_{\text{model}}^2}$$

$$\left( \frac{t_{\text{model}}}{t_{\text{mine}}} \right)^2 = \frac{l_{\text{model}}}{l_{\text{mine}}} = k$$

$$\frac{t_{\text{model}}}{t_{\text{mine}}} = t' = \sqrt{k}$$

The time scale factor is  $\sqrt{k}$ .

Thus the drawing rate scaling factor will be  $k^{2.5}$ .

It then can be concluded that it is impossible to expect physical models to achieve full similitude. However, as concluded by Power (2004) and comparison between JKMRC physical model and full scale test at He-Pei mine, a 1:30 scale model will yield results similar to the full scale ones.

There is a problem, however, with the 1:30 scale. The model can only simulate a maximum of 100m block height. It is also limited to a simulated draw area of 105m x 75m. These are not suitable for modern block caving mines, which have block height between 130 and 500m and draw area between 200m x 200m and 1km x 1km. The only way to overcome this limitation is reducing the scale to 1:100, which can simulate a maximum of 330m block height. This then puts a question on the similitude between this scale and the full scale.

A quantitative work on the effect of scale within physical models of a SLC mine was attempted by Ahlin (Haglund 1968). He carried out experiments on geometrically similar models at scales of 1:10, 1:50, and 1:100 with the aim of allowing the extrapolation of physical modelling experiments to full scale. Ahlin considered that the results of models run at different scales were not convertible to one another without correction. In general he found that the effect of scale was that axes shrank with diminishing model scale, despite all parameters being identically scaled to one another in the different experiments. For instance at 1:10 scale, Ahlin reported that one parameter measurement was 3m, while at 1:50 scale, the same parameter was 2.8m, and at 1:100, 2.6m. However, only one test was carried out at each scale. The approximately 15% difference between a scale of 1:10 and 1:100 quoted is within the dispersion found by Power (2004) on repeats of the same experiment. Quantification of any scale distortion from the results of Ahlin's work is therefore not possible.

Nevertheless, a research program has been proposed in JKMR to study the similitude of a 1:100 scale model. A method called *dimensionless analysis* has been considered as the best tool (Castro 2004) and will be used in that research.

### **3. Conclusions and recommendations**

Despite numerous works done in gravity flow field, 3D simulations of ore recovery and waste rock dilution can still not be done with confidence for conditions in a specific mine. Although some computer softwares have been developed, they remain unvalidated thus unreliable. Full scale tests, which are the best way to address this issue and also to obtain data for validating the softwares, are practically not feasible in block caving mines due to technical difficulties and costs. Therefore physical modelling remains as the best way for this purpose. It has been described in this paper that a large scale, at 1:30 or better, gravel model with multiple drawpoints is the best method of physical modelling. There are indications based upon sublevel caving geometries that the results from this model can be directly scaled to full scale for a block caving geometry. It has been thought that reducing scale of the model is essential for a block caving geometry since at 1:30 scale, the maximum block height that can be achieved is 100m, which is far below the heights in practice. Therefore, a study of scaling factor of a physical model at this scale is warranted.

### **4. Acknowledgement**

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## REFERENCES

- Alfaro, M., and Saavedra, J., 2004. "Predictive models for gravitational flow", in Proceedings MassMin 2004, Santiago, pp 179-184. Ed. A. Karzulovic and M. Alvaro. Instituto de Ingenieros de Chile, Santiago.
- Alvial, J., 1992. "Analysis of the extraction at Teniente 4 Sur LHD", in Proceedings MassMin 92, Johannesburg, pp 233-244. Ed. H.W. Glen. SAIMM, Johannesburg..
- Brady, B.H.G., and Brown, E.T., 1993. "Rock mechanics for underground mining", 2<sup>nd</sup> edition, pp 414-424. Chapman and Hall, London.
- Brown, E.T., 2002. "Block caving geomechanics", pp 255-259, Julius Kruttschnitt Mineral Research Centre, The University of Queensland, Brisbane.
- Carlson, G., Tyler, D., DeWolfe, C., and Lorig, L., 2004. "Understanding gravity flow for mix and dilution modeling at Henderson Mine", in Proceedings MassMin 2004, Santiago, pp 231-237. Ed. A. Karzulovic and M. Alvaro. Instituto de Ingenieros de Chile, Santiago.
- Castro, R., 2003. "Report of similitude and scaling in rock flow models", Julius Kruttschnitt Mineral Research Centre, The University of Queensland, Brisbane.
- Castro, R., 2004. "The scaling effects associated with the physical model of caving operations". Paper accepted for JKMR International Student Conference 2004, Brisbane.
- Chen, G., 1997. "Stochastic modelling of rock fragment flow under gravity", International Journal of Rock Mechanics and Mining Sciences, vol 34, no 2, pp 323-331.
- Chen, J. and Boshkov, S.H., 1981. "Recent developments and applications of bulk mining methods in the People Republic of China", in Design and Operation of Caving and Sublevel Stopping Mines, pp 393-418. Ed. D.R. Stewart. SME-AIME, New York
- Flores, G.E., 1993. "A new mining sequence to minimize stability problems in block caving mines", MSc thesis, Colorado School of Mines, Golden, Colorado.
- Flores, G.E., 2004. Personal communication about El Teniente 4 South mine design.
- Gustafsson, P., 1998. "Waste rock content variations during gravity flow in sublevel caving: Analysis of full scale experiments and numerical simulations," PhD thesis, Lulea University of Technology, Lulea, Sweden.
- Haff, P.K., 1983. "Grain flow as a fluid-mechanical phenomenon", J. Fluid Mech., vol 134, pp. 239-245.

Haglund, M. (Ed), 1968. "Skyvrasbrytnings Konferens I Malmberget 21 och 22 Maj, 1968", Protokoll G68-94, LKAB.

Hartman, H.L., 1987. "Introductory Mining Engineering", pp 444-445, John Wiley & Sons, New York.

Heslop, T.G., 1983. "The application of interactive draw theory to draw control practice in large chrysotile asbestos mine", in Mining and Metallurgical Operations in Zimbabwe, June 1983, Harare, Zimbabwe.

Heslop, T.G., and Laubscher, D.H., 1981. "Draw control in caving operations on Southern African Chrysotile Asbestos mines", in Design and Operation of Caving and Sublevel Stopping Mines, pp 775-774. Ed. D.R. Stewart. SME-AIME, New York.

Hollins, B. and Tucker, J., 2004. "Draw point analysis using a marker trial at the Perseverance Nickel Mine, Leinster, Western Australia", in Proceedings MassMin 2004, Santiago, pp 498-502. Ed. A. Karzulovic and M. Alvaro. Instituto de Ingenieros de Chile, Santiago.

Hustrulid, W. and Krauland, N., 2004. "Experiments regarding grain pressure in silos", translation of paper "Versuche Uber Getreidedruck in Silozellen" by H.A. Janssen 1895, in Proceedings MassMin 2004, Santiago, pp 293-300. Ed. A. Karzulovic and M. Alvaro. Instituto de Ingenieros de Chile, Santiago.

Hwang, H. and Hutter, K., 1995. "A new kinetic model for rapid granular flow", Continuum Mech. Thermodyn. vol. 7, pp. 357-384

Janelid, I., 1972. "Study of the gravity flow process in sublevel caving", in Proceedings of the International Sublevel Caving Symposium, Atlas Copco, Stockholm.

Janelid, I., and Kvapil, R., 1966. "Sublevel caving", International Journal of Rock Mechanics and Mining Sciences, vol 3, pp 129-153.

JKMRC, 2003. "International Caving Study II progress report, Flow research section", April. Confidential report to sponsors.

Julin, D.E., 1992. "Block caving", in SME Mining Engineering Handbook, pp 1815-1836. Ed. H.L. Hartman. SME, Littleton, Colorado.

Just, G.D., 1981. "The significance of material flow in mine design and production", in Design and Operation of Caving and Sublevel Stopping Mines, pp 715-728. Ed. D.R. Stewart. SME-AIME, New York.

Just, G.D., and Free, G.D., 1971. "The gravity flow of material in the sublevel caving mining system", in Proceedings of the 1<sup>st</sup> Australia-New Zealand Conference on Geomechanics, Melbourne, pp 88-97. Institution of Engineers, Australia, Sydney.

Just, G.D., Free, G.D., and Bishop, G.A., 1973. "Optimization of ring burden in sublevel caving", *International Journal of Rock Mechanics and Mining Sciences*, vol 10, pp 119-131.

Kvapil, R., 1965a. "Gravity flow of granular material in hoppers and bins Part 1", *International Journal of Rock Mechanics and Mining Sciences*, vol 2, pp 35-41.

Kvapil, R., 1965b. "Gravity flow of granular material in hoppers and bins Part 2", *International Journal of Rock Mechanics and Mining Sciences*, vol 2, pp 277-304.

Kvapil, R., 1992. "Sublevel Caving", in *SME Mining Engineering Handbook*, pp 1789-1814. Ed. H.L. Hartman. SME, Littleton, Colorado.

Laubscher, D.H., 1994. "Cave mining - the state of the art", *The Journal of the South African Institute of Mining and Metallurgy*, vol 94 no 10, pp 279-293.

Laubscher, D.H., 2000. "Block cave manual, design topic: drawpoint spacing and draw control". Julius Kruttschnitt Mineral Research Centre, The University of Queensland, Brisbane, Australia.

Lehman, G., 1916. "Ore-drawing tests and the resulting mining method of Inspiration Consolidated Copper Co.", *Trans. AIME*, vol 55, pp 218-231.

Mandel, J., 1963. "Tests on reduced scale models in soil mechanics and rock mechanics, a study of the conditions of similitude", *International Journal of Rock Mechanics and Mining Science*, vol 1, pp 31-42.

Marano, G., 1980. "The interaction between adjoining draw points in free flowing materials and its application to mining", *Chamber of Mines Journal, Zimbabwe*, pp 25-32.

McCormick, R. J. 1968. "How wide does a drawpoint draw?", *Engineering and Mining Journal*, June, pp 106-116.

McNicholas, F.S., Rogers, V.S., and Walker, M.S., 1946. "An experimental study of caving and drawing large ore bodies", *Trans. AIME*, vol 163, pp 156-197.

Nielsen, J. and Askegaard, V., 1977. "Scale errors in model tests on granular media with special reference to silo models", *Powder Technology*, vol 16, pp123-130.

Peters, D.C., 1984. "Physical modeling of the draw behavior of broken rock in caving", *Quarterly of the Colorado School of Mines*, vol 79 no 1.

Pierce, M., 2004. Personal communication about REBOP.

Power, G.R., 2004. "Modelling granular flow in caving mines: large scale physical modelling and full scale experiments", PhD thesis, The University of Queensland, Brisbane.



Quinteiro, C.R., Larsson, L., and Hustrulid, W.A., "Theory and practice of very large scale Sublevel Caving", in *Underground Mining Methods: Engineering Fundamentals and International Case Studies*, Ed. W.A. Hustrulid and R.L. Bullocks. SME, Littleton, Colorado, pp 381-394.

Richardson, M.P., 1981. "Area of draw influence and drawpoint spacing for block caving mines", in *Design and Operation of Caving and Sublevel Stopping Mines*, pp 149-156. Ed. D.R. Stewart. SME-AIME, New York.

Rustan, A., 1990. "The importance of using joints to achieve scaled fragmentation in magnetite concrete used for sublevel caving blast models", *Engineering Fracture Mechanics*, vol 35, no 1/2/3, pp 425-438.

Rustan, A., 2000. "Gravity flow of broken rock - what is known and unknown", in *Proceedings MassMin 2000*, Brisbane, pp 557-567. Ed. G. Chitombo. The AusIMM, Melbourne.

Sandstrom, P.O., 1972. "Application and optimization of sublevel caving techniques", *Engineering and Mining Journal*, June, pp 112-125.

Savage, S.B., and Hutter, K., 1989. "The motion of a finite mass of granular material down a rough incline", *J. Fluid Mech.*, vol 199, pp 177-215.

Sharrock, G., Beck, D., Booth, G., and Sandy, M., 2004. "Simulating gravity flow in sub-level caving with cellular automata", in *Proceedings MassMin 2004*, Santiago, pp 189-194. Ed. A. Karzulovic and M. Alvaro. Instituto de Ingenieros de Chile, Santiago.

Trueman, R., 2004. Personal communication about Peter Cundall and PFC3D.

Verdugo, R. and Ubilla, J., 2004." Geotechnical analysis of gravity flow during block caving", in *Proceedings MassMin 2004*, Santiago, pp 195-200. Ed. A. Karzulovic and M. Alvaro. Instituto de Ingenieros de Chile, Santiago.