A study of isolated draw zones in block caving mines by means of a large 3D physical model

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Abstract

Block caving methods rely on gravity to break and transport large amounts of ore and waste. Despite the importance of gravity flow, there is debate within the literature about the influence that the height of draw, particle size and particle size distribution has on the geometry of extraction and movement zones. This paper presents the results of an experimental programme conducted in the largest three-dimensional (3D) physical model to investigate the mechanisms of flow of cohesionless materials when drawing from a single drawpoint. Experimental results showed that isolated draw zones are mainly influenced by mass drawn and height of draw. Particle size was found to have a slight effect on extraction zones and no significant effect on movement zone width. Particle size composition (wide or narrow distributions) and drawpoint width were found not to have a major role on drawzone geometry. Those conclusions were based on statistical analysis of experimental data to define the controlling parameters in isolated draw. Model theory principles were used to investigate within the physical modelling framework the possibility of directly scaling the geometry of the extraction zones, which indicated that flow zones could be scaled in cohesionless materials under a set of assumptions. A mechanistic model of isolated draw is also postulated from experimental data from observations of stresses and the IMZ's geometry.

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1. Introduction

Block caving refers to mass mining methods in which the ore body caves naturally after undercutting and the caved ore is recovered through drawpoints. These include block caving, panel caving and its variations. These methods currently have the lowest operational costs and highest productivity in underground mining [1].

The cost effectiveness of a block caving operation relies strongly on the use of gravity to both cave and transport large amounts of broken rock from its *in situ* location. In block caving methods, the ore and the waste caves under the influence of gravity and the redistributed *in situ* stresses after the undercutting of the orebody base. As material is extracted, the cave front propagates upwards until the overlying rock also caves and surface subsidence occurs.

The caving process transforms the initially *in situ* solid rock into a broken rock mass, which flows towards the drawpoints as it is extracted by mechanised equipment at drawpoints located in the production level [2].

Due to the high initial capital investment of a block cave and its lack of flexibility, it is critical for the success of caving mines to achieve an economically acceptable level of ore recovery and dilution content when in operation. Ore recovery and dilution in a block caving operation are strongly determined by the design and performance of the production level and the flow characteristics of the ore and waste material [3].

Research on gravity flow has mainly focused on understanding the mechanisms involved and their impact on the design and operation of the mine's production level. Despite its importance and the substantial research work, gravity flow mechanisms of the caved ore are still not well understood [4]. This paper attempts to address some of the questions raised in the literature by using a Large three-dimensional (3D) Physical Model built at The University

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2. Previous work

The flow characteristics of the caved rock in block caving have been studied through physical and numerical models and full-scale trials [5–17]. There is consensus in the literature that the gravity flow of a granular medium generates two definite zones: the extraction zone formed by the removed material and the movement zone formed by the material under flow [9,10]. The majority of researchers have concluded that the shape of extraction and movement zones is ellipsoidal and called the zones accordingly [9–16]. Others have observed that the extraction zone geometry follows other shapes [4,6]. In this paper, in order to avoid reference to a particular shape of the flow zones when a point of draw is worked in isolation, we use the term isolated extraction zone (IEZ) to refer to the extracted zone; and isolated movement zone (IMZ), to refer to the volume that defines the flowing material.

To date most of the current understanding of the mechanics of isolated draw has been gained through physical modelling due to the practical difficulties in directly observing the caved rock flow *in situ*. Despite a considerable research effort, there is still debate in the literature about the controlling parameters on isolated draw in block caving. For example, McCormick [13] observed in small sand models that the IMZ followed a cylindrical shape and reached a constant width with extraction. He concluded that particle size and drawpoint width had a minimal effect on the maximum IMZ's width. Marano [12] and others [14,15] later conducted tests on large 3D sand models and concluded that the IMZ has a cylindrical shape and reached a maximum width soon after the start of draw. Marano's tests were used by Laubscher [2,3] to propose a guideline for the design of production levels in block caves based on the geometry of the IMZ.

Experiments measuring IEZs using gravel as the model media have been carried out in order to understand the flow of coarse caved rock [6,16]. Peters [7] concluded that particle size had a small effect on the IEZ width and indicated that the drawpoint width dimensions have a major role in determining its geometry. Peters observed that the extraction zones in gravel were not elliptical as described by Kvapil, but were elongated in the centre; he observed that the IEZ reached a maximum width with extraction. Power [16] who conducted 3D modelling using gravel, found that the height of draw and particle size had a strong effect on IEZ's geometry.

In this paper, the authors present a study of the controlling parameters in isolated draw for the flow of coarse caved rock from the results of experiments in the largest 3D physical model ever constructed to study gravity flow in caving mines. Statistical analyses on the data were carried out to help delineate the controlling parameters

under those conditions. As a first step towards that objective, a study of similitude between the large physical model set up and the prototype (mine) was carried out.

3. Analysis of similitude

The gravity flow of caved rock in block caving is a very complex process. The rock mass that is initially in a solid state becomes a fragmented mass by the action of stresses due to the caving process, that is, the primary fragmentation process. Afterwards, the caved rock is removed through drawpoints. As materials flows, secondary fragmentation of the rock through point loading and abrasion mechanisms takes place. Additionally, factors such as water intrusion, high level of fine fragmented rock and large stresses could potentially have a strong effect on material strength behaviour and therefore on its gravity flow characteristics. In order to physically model the flow of caved rock, a simplified version of the process was established which incorporates the following simplifications and assumptions: (a) gravity flow in caving mines involves the study of non-cohesive, coarse fragments, moving slowly under the action of gravity. (b) The granular mass is heterogenous but isotropic. (c) The granular flow occurs in a 3D environment without any special weak boundaries. (d) Rock breakage mechanisms, primary and secondary breakage, are not considered.

For the stipulated assumptions, an analysis of similitude showed that the gravity flow patterns observed in two different geometrical scaled models will be similar if the following conditions hold. (1) There is geometrical similitude for the whole block geometry. That includes block dimensions (height and area of draw), drawpoint dimensions, particle size distribution and particle shape. (2) Gravity and bulk density in the model and prototype are the same: $\lambda_\rho = \lambda_g = 1$. (3) The scale of times is related to that of the length by $\lambda_t = \lambda_l^{1/2}$. (4) The scale of stresses is related to that of lengths by $\lambda_\sigma = \lambda_r = \lambda_l$. (5) The residual friction angles are the same: $\lambda_{\phi_r} = 1$. (6) Wall friction angle are similar to the internal friction angle: $\phi_w = \phi$, where λ is the scale factor for each of the variables under study. During this study, the above hypothesis of scaling was tested by carrying out experiments at two different geometrical scales.

4. Experimental description

The large physical model was designed to run simulations of flow for block caving under both isolated draw and interactive draw conditions. Variations of design parameters such as drawpoint dimensions were also incorporated in the design. The physical model main assembly is 3.5 m wide, 2.5 m long, and 3.3 m high. It holds approximately 55 tonnes of aggregate. This represents the largest 3D physical model ever constructed to study flow in block caving using gravel as the model media (see Fig. 1).

Fig. 1. Large three-dimensional JKMRC physical model.

The physical model was configured to represent modern block cave geometries using two different geometrical scales 1:30 and 1:100. The dimensions in the model were determined after conducting a benchmark of current mine design practise [18]. At these scales the physical model attempted to represent the flow of coarse fragmented caved rock having a mean size of 0.7 m and a height of draw of 100–330 m. The model height was 3300 mm and draw point dimensions were 120 mm wide $\times$ 100 mm high and 36 $\times$ 30 mm accordingly. For the isolated draw experiments, drawpoints were located in the centre of the model's base so the flow zones did not intersect the model's walls.

Material was extracted using a vibrational loader so that it was not in contact with the model, preventing vibrations from affecting the flow. This system allowed material to be drawn remotely from beneath the model and fed onto a series of conveyors which transported it to a weigh point. The vibrational loader was designed and comparisons were made between extracting material using a model bucket and the vibrational loader with no difference being noted.

Refilling of the model was performed after the IMZ had reached the surface. This had the objective of preventing material riling towards the crater and of maintaining a constant level of vertical stresses. Thus, the maximum height of the IEZ referred to in this paper is that at which

the markers located at full height arrived at the drawpoint, which occurred after recycling gravel on the model's top.

4.1. Model media

The tests described in this paper were conducted using crushed phyllite gravel purchased from a local quarry. The gravel was air dried prior to being used in the experiments. This had the objective of avoiding cohesion due to capillary effects on the material's fine fraction. During the experimental phase, two different media were tested, one using a narrow distribution (8 mm-ND) and another using a wide size distribution (18 mm-WD) of particle sizes. Additional to those tests, experiments on IEZs for a 20 mm narrow distribution media conducted by Power [16] were incorporated in the analysis. The cumulative size distribution for the different particle sizes is presented in Fig. 2.

The shear strength characteristics of the different media tested were determined using a large 300 mm diameter shear box. Samples were subjected to different normal forces ranging from 32 to 240 kPa, and results are presented in Fig. 3. Repeats of the shear strength tests showed that the error in the estimate of the friction angle was 1.5°. The results suggest that friction angle slightly increased with particle size.

Other properties of the media under study were measured and are summarised in Table 1. In this, the uniformity index of the distribution C_u is defined as

$$C_u = \frac{p_{60}}{p_{10}}, \quad (1)$$

where p_{10} is the size corresponding to the 10% passing and the p_{60} is the 60% passing size. The rock shape factor is calculated by [19]

$$r_v = \frac{6V}{\pi d^3}, \quad (2)$$

where V is the mean volume of a particle and d is the mean particle diameter calculated from the arithmetic mean of width, length and depth of a particle.

Fig. 2. Size distribution of material for different particle size distributions under study.

Fig. 3. Maximum shear strength for different particle sizes.

Table 1
Summary of model media characteristics used during experiments

Material	p_{50} , mm	C_u	ϕ	Solid/bulk density, Ton/m ³	Size fraction, mm	Aspect ratio ($w:l:d$), mm	Shape factor r_v
WD-18 mm	16.8	2.33	45	2.7/1.9	19	32:24:14	0.78 (± 0.17)
					9.5	13:9:3	0.75 (± 0.13)
					3.5	7:5:3	0.82 (± 0.28)
ND-8 mm	8.3	1.53	41	2.70/1.55	13:9:6		0.81 (± 0.14)
ND-20 mm	20	1.21	46	2.71/1.5	32:20:13		0.84 (± 0.47)

4.2. Measurement devices

Because of the 3D configuration of the physical model, material was surrounded on all sides and thus modelling was, in effect, blind. In order to determine the extraction zone, painted numbered markers were positioned inside the model and recovered at the drawpoint (Fig. 4a).

However, only the geometry of the extraction zone for a given mass drawn could be deduced from the system of markers. For that reason, sensors were developed in order to determine the movement zone. The movement probes are of an extensometer configuration (Fig. 4b). A length of piano wire slides inside a length of brass tube, propelled by the internal spring of a microswitch. The frictional force between the sliding wire and tube is just low enough for the microswitch to move the piano wire forward when the assembly is horizontal. Adjustment is provided so that the piano wire can be set relative to the end of the tube when held back by a particle. The movement probes are designed to detect the beginning of movement of the particle directly in front of the probe tip. Prior to installation, the sensors were tested in a 2D model from where the flow contour could be observed and calibrated.

Sensors were positioned within the model at five different levels to determine the evolution of the IMZ with mass drawn. The spacing of sensors in the horizontal was 50 mm for the fine and 100 mm for the coarser fragmented material. In order to avoid flow interference, the number of

sensors was significantly less than the number of markers used to determine the IEZ.

5. Experimental results

Experiments were carried out to investigate the effect that the height of draw, particle size, particle size distribution and drawpoint dimensions have on flow zone dimensions. Table 2 presents a summary of the database used to investigate the controlling parameters on isolated draw.

5.1. Effect of height of draw

Figs. 5 and 6 show typical results of the isolated extraction and movement zones for different accumulated mass drawn. This figure corresponds to a vertical section passing through the middle of the drawpoint of the respective 3D flow geometry. It is observed that the geometry of the width of extraction and movement zones increases with the height of IEZ and IMZ, respectively.

The IMZ reaches the surface of the model well before the IEZ; and it is always wider and higher than the IEZ for a given mass drawn. The IEZs and IMZs could be reasonably well fitted by an ellipsoid contour. The smoothness of the IEZ profile is different to that of the movement zone due to the larger number of labelled markers compared to movement sensors.

5.2. Effect of particle size

Fig. 7 presents the extraction zone widths for different particle sizes as a function of the height of draw. In this graph, we plotted the 95% confidence interval for the estimate of the width of the IEZ's for the 20mm-ND media. Within that range, the widths of the IEZ for all

Fig. 4. (a) Example of marker used to determine extraction zone; Marker is 20 mm passing size; (b) modified extensometer used to detect the movement envelope.

Table 2
Summary of experimental set up

Experiment	Model media (mm)	Drawpoint dimensions $dp_w \times dp_h$, mm	Geometrical scale λ_L	Height filled h_f , mm	dp_w/p_{50}	h_f/p_{50}
T1	ND-20	120 × 100	1:30	3300	6	165
T2	ND-20	120 × 100	1:30	3300	6	165
T3	ND-8	36 × 30	1:100	3300	4.5	413
T4	ND-8	36 × 30	1:100	3300	4.5	413
T5	ND-8	36 × 30	1:100	3300	4.5	413
T6	ND-8	120 × 100	1:30	3300	15	423
T7	WD-18	120 × 100	1:30	3300	6.7	183
T8	WD-18	120 × 100	1:30	3300	6.7	183
T9	WD-18	120 × 100	1:30	3300	6.7	183

Fig. 5. Vertical view of extraction zone for the (a) 8 mm-ND; (b) 18 mm-WD particle size distributions.

Fig. 6. Movement zone for 8 mm-ND model media before and after the IMZ reached the surface.

media size were similar for heights of draw below 3000 mm. At 3000 mm, that is, close to the end of the experiment, the 8 mm-WD and the 18 mm-WD media were slightly narrower (~ 100 mm) than the IEZ's width of the 20 mm-ND media.

The average IMZ's width for two different media is presented in Fig. 8. The calculated IMZ's width standard deviations were 53 and 23 mm for the 18 mm-WD and 8 mm-ND media, respectively. The large data dispersion for the wide distribution was expected given the larger spacing (100 versus 50 mm in the horizontal plane) that had to be used to determine the movement envelope in the coarser material. The analysis shown in Fig. 8 indicated that there was no statistical evidence to conclude that the width of the IMZ between the two media differed significantly.

Fig. 7. IEZ's width measured at different height and particle sizes. The 95% confidence bound for the width of the 20 mm-ND had been included.

Fig. 8. IMZ's width as a function of IMZ's height for different particle size distributions. The mean and error band at 95% confidence interval had been included.

5.3. Effect of drawpoint dimensions

The effect of drawpoint width on draw geometry was investigated using two different drawpoint geometries. Given the size of the experimental set up here described, it was not feasible to carry out repeat tests on $120 \text{ mm} \times 100 \text{ mm}$ drawpoint dimensions. However it was possible to statistically test if the drawpoint dimensions affected the flow zones using the experimental errors calculated from previous tests. Tables 3 and 4 show the results of the extracted area and the width of IMZ measured at different heights (h_i). In this analysis we included the mean values and standard deviation (in brackets) corresponding to three tests using a $36 \times 30 \text{ mm}$ drawpoint dimension and a single test using a $120 \times 100 \text{ mm}$ drawpoint. Given the experimental errors,

Table 3
Effect of drawpoint width on the IEZ's geometry

IEZ height, mm	h_i , mm	IEZ area ($dp_w = 36$ mm), mm ²	IEZ area ($dp_w = 120$ mm), mm ²	Difference mm ²
3300	2400	397,400 (21,779)	382,000	15,400
	1600	493,400 (8202)	487,600	5800
	800	307,600 (3960)	310,400	−2800
2000	1500	238,800 (8485)	244,800	−6000
	1000	281,000 (1414)	282,000	−1000
	500	129,200 (2263)	127,600	1600
1000	750	79,600 (8445)	73,600	6000
	500	74,600 (4283)	71,600	3000
	250	37,800 (283)	37,600	200

Table 4
Effect of drawpoint width on IMZ's geometry

IMZ height, mm	h_i , mm	IMZ's width w_{IMZ} ($dp_w = 36$ mm), mm	IMZ's width w_{IMZ} ($dp_w = 120$ mm), mm	w_{IMZ} ($dp_w = 36$ mm) w_{IMZ} ($dp_w = 120$ mm), mm
3300	2400	577 (±31)	540	37
	1600	627 (±21)	600	27
	800	557 (±21)	500	57
2000	1500	467 (±15)	380	87
	1000	480 (±30)	390	90
	500	367 (±23)	350	17
1000	750	247 (±21)	230	17
	500	257 (±35)	260	−3
	250	187 (±15)	220	−33

it was concluded that there is no significant difference in both extracted area and the IMZ width for the range of drawpoint dimensions under study.

5.4. Effect of model scale

One of the most difficult questions that physical modellers face after they have carried out experiments at reduced scale is the meaning and transfer of quantitative results to industrial applications. This is more crucial in block caving given the lack of quantitative full-scale data from which it could be possible to compare scaled values. A way of addressing this problem is through the application of model theory. Model theory states that a quantitative result would be scalable as long as the governing phenomena equations are the same between the scaled model and the prototype [20]. In other words, input and output dimensionless quantities between model and prototype are kept constant.

The isolated draw tests carried out using a range of drawpoint dimensions and particle sizes enabled us to study the effect of scale on the IEZ geometries. If there is distortion or it is not possible to scale the geometry of the IEZ between different scaled models, a reduction in the geometrical scale factors would result in significant differences between dimensionless IEZ geometries. We postulate that in the flow of cohesionless materials, under the set of assumptions stated in Section 3, gravity flow

would be determined by the following dimensionless parameters:

$$\pi_1 = \frac{h_{IEZ}}{d_p}, \pi_2 = \frac{w_{IEZ}}{d_p}, \pi_3 = \frac{dp_w}{d_p}, \tag{3}$$

where d_p is a characteristic particle size and h_{IEZ} , w_{IEZ} are the height and width of the IEZ and dp_w is the drawpoint's width. The characteristic particle size p_{50} was used as experiments conducted in [16] and those presented here showed no particular change in IEZ or IMZ width.

In our experiments the drawpoint dimensions and the particle size were varied according to two different geometrical scale models, 1:100 and 1:30. By reducing simultaneously the size of the particles and the drawpoint dimensions, the dimensionless $\pi_3 = dp_w/d_{50} \sim 6$ was constant between the two scales. This meant that, the small-particle-drawpoint-width dimensions experiments were a scaled model (1:3) of the large-fragment-size-drawpoint-width experiment. As noted in the value of π_3 , the particle size used, represents a relatively coarse fragmentation when compared to the drawpoint width dimensions, which resulted in intermittent mechanical hang ups at the drawpoint.

Fig. 9 shows the dimensionless width π_2 as a function of the dimensionless extracted heights π_1 measured in the two-scaled models. It is noted that π_2 is a linear function of π_1 for the range of heights under study. The analysis of error as shown in Fig. 6 concluded that the change in geometrical

scale did not change the dimensionless extraction width. This indicated that for cohesionless materials, the geometry of the IEZ was comparable between different geometrical scales, at least for the ranges studied.

6. Granular flow mechanisms

The controlling mechanisms of isolated draw were studied by observing the change in the geometry of the IMZ at different stages of draw together with direct stress measurements. Previous research conducted with numerical models [5] has postulated that the IMZ was controlled by two different mechanisms: collapse of an arch and erosion at the sides, as material is drawn. In this part of the paper we investigated the isolated draw mechanisms based on experimental observations.

As it is shown in Figs. 10 and 11, the overall geometry of the IMZ and IEZ is mainly controlled by the mass drawn. We noticed that the geometry of the IMZ did not change if material was not being drawn. It was observed that the rate of growth of the IMZ's height as a function of mass drawn

decreases during extraction and reached a constant value. The relationship between the IMZ height (h_{IMZ}) and the accumulated mass drawn (m) was fitted by an equation of the form

$$h_{IMZ}(m) = h_0(1 - e^{-m/m_h}) + cm, \quad (4)$$

where h_0 and m_h represents the height and mass at which the IMZ's height increases exponentially with mass; and c is the final rate of growth when the height grows linearly with the mass drawn.

The IMZ is by definition a zone within the granular material that has undergone an increase in porosity. Measurements of stresses showed that immediately above the IMZ's height there is a zone of high horizontal stresses. It is postulated that this higher horizontal stressed zone identifies a stress arch that separates the lower (final) and higher (initial) porosity zones. Eq. (4) shows that the rate of collapse of this arch grew rapidly at the initiation of draw and reached a constant collapse rate c when m_0 kg had been drawn. The values of the fitted coefficients and the correlation coefficient of the non-linear model are shown in Table 5. These values were obtained using the non-linear Levenberg–Marquardt regression method. It is interesting to note that although the IEZ could not strictly be used to understand mechanisms; the IEZ's width could be fitted using Eq. (4). However, as shown in Table 5 the fitted coefficients for the IEZ are an order of magnitude larger than those of the IMZ.

In Fig. 11, the change on the IMZ and IEZ's width with mass drawn is plotted. The analysis showed that the width of both zones increased with the mass drawn. The rate of expansion of the IMZ's width decreased with accumulated mass drawn. We observed that the horizontal expansion of the IMZ with the mass drawn occurred in two separate stages. The first stage occurred when the IMZ was fully contained within the boundaries of the model and the second stage occurred after the IMZ broke through to the surface. The relationship between the width of the IMZ and the mass drawn was shown to be non-linear and be

Fig. 9. Dimensionless IEZ's width as a function of the dimensionless IEZ's height.

Fig. 10. IMZ's height as a function of the accumulated mass draw for the 8 mm-ND media.

Fig. 11. Maximum width of IMZ and IEZ as a function of the mass drawn for the 8 mm-ND for $dp_w = 36$ mm.

Table 5
Eq. (4) parameters for material under study

Media	Flow zone	h_0 , mm	m_h , Kg	c , mm/Kg	R^2
8 mm-ND	IMZ	1225 (± 164)	20.8 (± 7)	9.2 (± 1.04)	0.96
18 mm-WD	IMZ	2087 (± 1020)	65.8 (± 21.4)	3.73 (± 1.59)	0.97
8 mm-ND	IEZ	1424 (± 70)	140 (± 21)	0.98 (± 0.06)	0.99
18 mm-WD	IEZ	1480 (± 63)	159 (± 20)	0.87 (± 0.04)	0.99
20 mm-WD	IEZ	1578 (± 52)	194 (± 18)	0.68 (± 0.03)	0.99

Table 6
Eq. (5) parameters for material under study

Media	Flow zone	w_0 , mm	m_1 , Kg	m_2 , Kg	β	R^2
8 mm-ND	IMZ	1004 (± 16)	40 (± 3.8)	775 (± 74)	0.47 (± 0.01)	0.97
18 mm-WD	IMZ	1216 (± 154)	54.2 (± 14)	1285 (± 443)	0.31 (± 0.02)	0.94
8 mm-ND	IEZ	770 (± 10)	17.2 (± 3.4)	584 (± 25)	0.26 (± 0.01)	0.99
18 mm-WD	IEZ	779 (± 47)	86.2 (± 58)	887 (± 243)	0.24 (± 0.08)	0.98
20 mm-WD	IEZ	1183 (± 382)	138 (± 75)	2263 (± 1987)	0.29 (± 0.04)	0.94

well fitted by a relation of the type

$$w_{IMZ}(m) = w_0(1 - \beta e^{-m/m_1} - (1 - \beta)e^{-m/m_2}), \quad (5)$$

where w_0 is the maximum width after the IMZ reached the surface, β is an adjusting constant (dimensionless) and m_1 , m_2 are the masses identifying the two stages on the IMZ's width expansion. The values of the fitted constants and the statistical analysis of the fitted parameters are presented in Table 6. As with the previous relationship, the IEZ's width could be fitted with a similar function.

The change in the width of the movement zones with height is shown in Fig. 12. In this case we have included the derivative (dw_{IMZ}/dh_{IMZ}) to show the change in the rate of expansion of the IMZ's width with height. This shows that w_{IMZ} increases with h_{IMZ} irrespective of particle size. However, the rate at which the width increases with height decreases as the IMZ moves towards the surface. A good fit

to the width in terms of the height is given by the following expression:

$$w_{IMZ}(h_{IMZ}) = ah_{IMZ} - \frac{b}{\alpha} \left(\frac{1 + e^{\alpha(h_{IMZ}-h_0)}}{1 + e^{\alpha h_0}} \right), \quad (6)$$

where a and b are positive dimensionless constants, α is in mm^{-1} and h_0 is the inflexion point in terms of height which the rate of horizontal expansion decreases. There are two terms in Eq. (6); a linear and an exponential decay that could be used as a means of interpreting the overall geometry change during draw. In the initial stage of draw, the width increases at a rate of $(a+b)$ mm per each mm in height. After the IMZ had reached a critical height h_0 there is a decrease in the rate of expansion. The parameter α is an adjustment parameter that defines the rate in which the final stage is reached. The fitted coefficients for the data obtained are presented in Table 7.

Fig. 12. IMZ's width as a function of the IMZ's height.

Table 7
Eq. (6) parameters for different media

Media	a	b	$\alpha \text{ (mm}^{-1}) \times 10^{-2}$	$h_0, \text{ mm}$	R^2
8 mm-ND	$0.08 (\pm 0.03)$	$0.18 (\pm 0.05)$	$4.37 (\pm 0.36)$	$2054 (\pm 224)$	0.98
18 mm-WD	$0.13 (\pm 0.02)$	$0.06 (\pm 0.042)$	$9.9 (\pm 12000)$	$1564 (\pm 866)$	0.89

7. Conclusions

There is debate within the literature about the effect that particle size and height of draw has on the isolated extraction and movement zone geometries. Experiments were carried out in a Large Physical Model in order to investigate the influence of those variables on the gravity flow of cohesionless materials. The results suggest that the main variables that affect the geometry of flow zones are the mass drawn and the height of draw. Within the precision and range of particle sizes of our experiments, it was observed that particle size only had a small effect upon extraction and movement zone widths. More experiments at small fraction sizes where the friction angle and particle shape are constant, would be beneficial in order to determine the values at which particle size may have a significant effect on flow geometries. The drawpoint width and the size composition (wide or narrow distribution of sizes) were found to have a negligible effect on draw zone geometries.

These experiments allow a better understanding of the mechanism involved in isolated draw. It was experimentally observed that the IMZ height is controlled by a stress arch zone that collapses as material is drawn. The IMZ's width increases by continual erosion of its boundaries as material is being drawn. Quantitative values for erosion and collapse rates were calculated for different media tested and were shown to change during the extraction.

Research on the influence that a change in geometric scale has on extraction zones was conducted. This suggests that the results from a 1:100 model could be used to obtain those in a 1:30 scale. While recognising the greater complexity of granular flow at full scale when compared

to model scale, results describing no significant distortions between scales are encouraging and may open the possibility to extrapolate results from model scale to full scale.

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