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Experimental investigation of stress redistribution in high draw columns for deep caving operations

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Abstract

The deepening of mining deposits, particularly those exploiting block/panel caving methods, requires an improved understanding of stress conditions and gravity flow dynamics, which remain relatively understudied when compared to shallower caving environments. Therefore, dedicated efforts are needed to investigate gravity flow behaviour in deep mining to design viable operations with reduced uncertainty. This study presents large-scale physical model experiments designed to investigate stress redistribution during gravity flow in a 600 m equivalent draw column under different extraction strategies. Two extraction configurations were evaluated: isolated draw from a single drawpoint and multiple draw under a near-uniform extraction scheme. Vertical stresses acting on the crown pillar were monitored using load cells installed at the base of the model.

The results show that stresses decrease significantly within active movement zones, reaching values as low as 40% of the initial vertical stress near isolated drawpoints. In contrast, stresses increase in adjacent low-extraction or stagnant regions due to stress transfer from active flow zones. Under multiple-draw conditions, relatively small differences in extraction between neighbouring drawpoints produced substantial stress variations, with local stresses reaching up to 1.6 times the initial stress. These findings demonstrate the strong influence of draw control on stress redistribution and highlight the importance of maintaining extraction uniformity to support production-level stability in deep caving operations.

Keywords: *block caving, gravity flow, high column, deep mining*

1 Introduction

The mining industry is continuously facing significant challenges in the current environment, including deeper deposits, more competent rock masses, higher in situ stresses, increasing production demands, and rising capital and operating costs. In the context of block/panel caving, these conditions require deeper cave propagation, as well as higher standards in safety and productivity, to ensure economic viability (Flores-Gonzalez 2019). At greater depths, the height of the extraction column also increases, imposing additional loads on the production level during ore extraction (Castro et al. 2020; Pierce 2019). This phenomenon has been associated with reported damage at the production level (Quiñones et al. 2014; Rodríguez et al. 2020; Rojas et al. 2000; Viegas et al. 2018), which may be further exacerbated by high extraction columns and inadequate draw control.

At the production level of a block/panel caving operation, the stress state after cave propagation is governed by the overburden of the broken material and its flow behaviour. Several gravitational flow experiments in caving environments have quantified these stresses (Castro 2007; Castro et al. 2020; Gómez & Castro 2022; Orellana 2012), showing how material extraction and the formation of distinct flow zones generate induced

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stresses during draw. Both experimental and numerical studies have demonstrated that stresses can be transferred from the movement zone to the stagnant zone during flow. In general, stresses within the movement zone tend to be lower than those in the surrounding stagnant material. Additionally, in caving mines, the extraction sequence varies depending on the mining strategy employed, leading to different induced stress responses.

Despite these advances, studies addressing high extraction columns in caving operations remain limited. Therefore, the objective of this research is to analyse, through laboratory-scale experiments, the impact of high columns on induced stresses under different extraction sequences. This study contributes to a better understanding of stress development in high extraction columns by providing controlled experimental evidence under two draw strategies. The results aim to support the design and operation of production levels in deep caving environments, particularly in terms of draw control and stability management.

2 Methodology

2.1 Physical scale model and materials

To address the problem described above, large-scale gravitational flow experiments with significant vertical extent are proposed using a physical model. Geometrically scaled broken material is employed, and different extraction scenarios are defined to quantify the stresses generated at the base of the model for high extraction columns above the crown pillar. The physical model represents a Teniente-type layout at the extraction level, with dimensions of 32 × 20 m and a total area of 16,640 m². The model walls were constructed using acrylic, which enabled clear visualisation of the movement zones within the model (Figure 1).

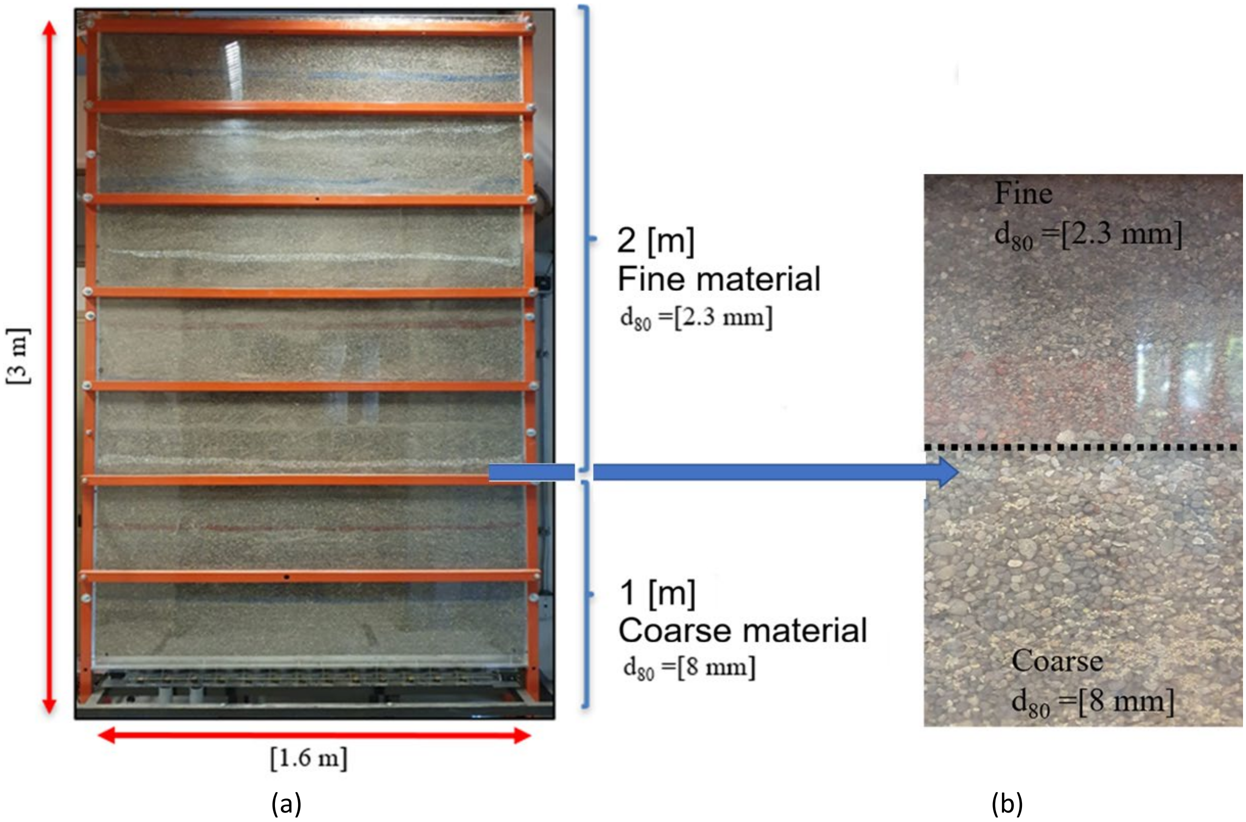


Figure 1 (a) Front view of the physical model used in this study loaded with crushed ore; (b) Zoom in on the interface of fine and coarse materials loaded into the model

The model has a width of 0.34 m, a length of 1.6 m and a height of 3 m. This height represents a 600 m extraction column at mine scale (1:200). To measure stresses, load cells were installed on the crown pillar (see Figure 2) and their distribution was varied according to the set-up used in each experiment. In addition, labelled markers were used to characterise the dimensions of the movement and extraction ellipses (Figure 3).

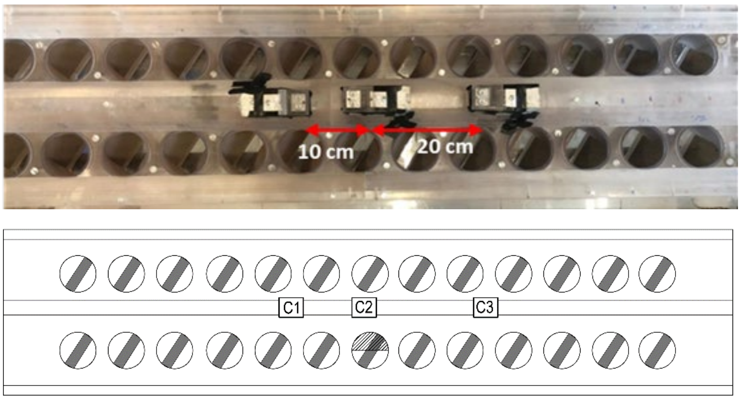


Figure 2 Plan view of the production level showing the location of the load cells at the centre of the crown pillar. The circular drawbells used in this study are also illustrated

The extraction zone corresponds to the material that has been drawn at a given stage of extraction (Hustrulid & Kvapil 2008). This zone is identified using markers made from ore painted in different colours, with the same particle size distribution as the coarse material, according to their initial placement height within the model (Figure 3). Each marker was positioned inside the broken ore (Figure 3b). Movement markers were used to delineate movement zones, while extraction markers were used to define extraction zones.

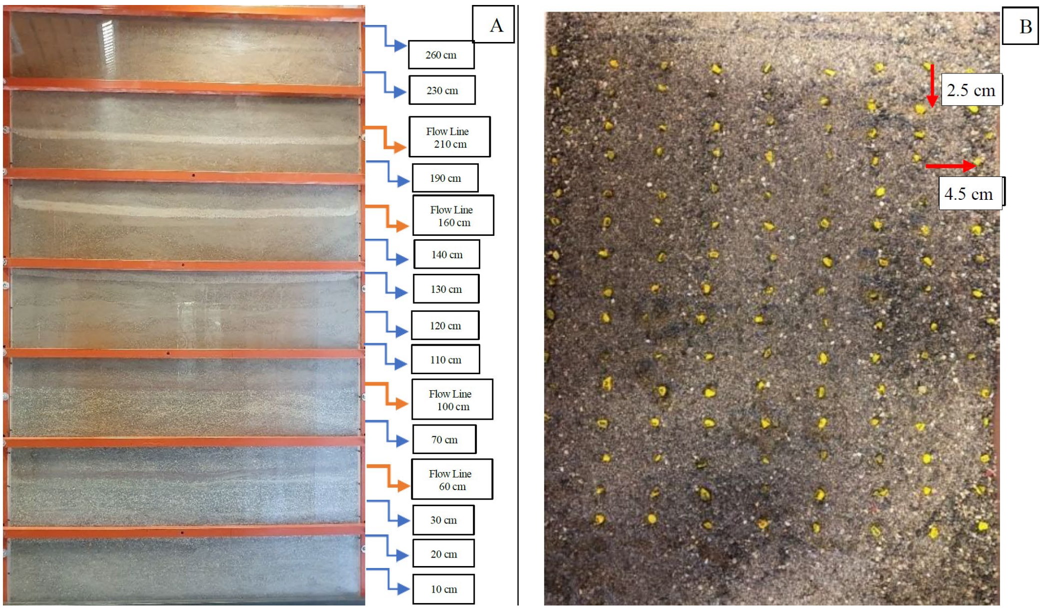


Figure 3 (a) Front view showing the vertical distribution of the different markers used; (b) Plan view of the installation of extraction markers (yellow)

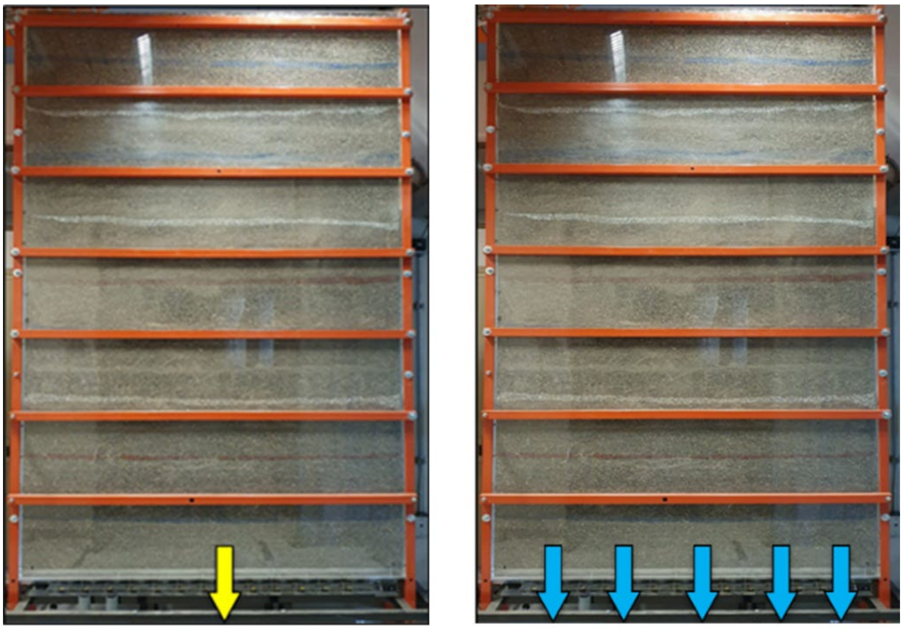
The material used in the experiments consisted of gravel, which was divided into coarse and fine fractions. The characteristic particle sizes of both distributions followed a size ratio of 1:3, with d_{80} values of 8.0 mm for the coarse fraction and 2.3 mm for the fine fraction. Table 1 summarises the main properties of the material, as well as the particle size distributions used in the physical model. Both the physical model and the granular material used in the experiments were geometrically scaled at a ratio of 1:200. The gravel was prepared using the parallel gradation method (Marachi 1969) to replicate a representative field particle size distribution while reducing maximum particle size for laboratory-scale testing.

Table 1 Material properties used in the experiments

Parameter	Coarse material	Fine material	Unit
d_{80}	8.0	2.3	mm
Mean size, d_{50}	4.5	1.0	mm
Ore density	2,600	2,600	kg/m^3
Bulk density	1,600	1,500	kg/m^3
Coefficient of uniformity (Cu)	4.8	2.7	–
Repose angle	30.6	31	°
Internal friction angle	48	42	°
Swell factor	0.58	0.62	%
Porosity	47	48	%

2.2 Experimental procedure

The experimental plan was defined based on the variables under study. In this case, two experiments were conducted with different objectives. Both experiments were conducted with a column height of 600 m (3 m at laboratory scale). In experiment 1, an isolated draw was performed from a central drawpoint (Figure 4a), allowing the evolution of the isolated movement zone to be characterised during extraction. In experiment 2, a uniform multiple draw configuration was applied (Figure 4b), enabling the assessment of vertical stress behaviour under uniform extraction conditions. In uniform extraction, material was taken simultaneously from all drawpoints, maintaining an approximately uniform extraction mass per drawpoint during each extraction interval.



(a) (b)

Figure 4 (a) Isolated draw strategy; (b) Multiple draw strategy (uniform)

The experimental procedure involves material preparation, as well as the calibration and installation of the required instrumentation (load cells and extraction systems). Experiment 1 corresponds to an initial trial conducted under an isolated flow configuration, while experiment 2 involves multiple extraction.

Each experiment requires approximately 60 days to complete and uses more than 200 kg extracted from experiment 1 and approximately 800 kg extracted from experiment 2. The material distribution consists of coarse material within the first metre of height, with the remaining two metres filled with fine material (Figure 1). The position of the load cells varied for each experiment.

3 Results

3.1 Experiment 1: isolated draw

The configuration of experiment 1 consists of an isolated draw of the broken ore column. Material extraction was carried out until markers from the uppermost layer were recovered. In addition, the evolution of the isolated movement zone (IMZ) was monitored until it reached the surface, which occurred after extracting 25.5 kg, corresponding to 5% of the total 510 kg extracted in experiment 1 (Figure 5).

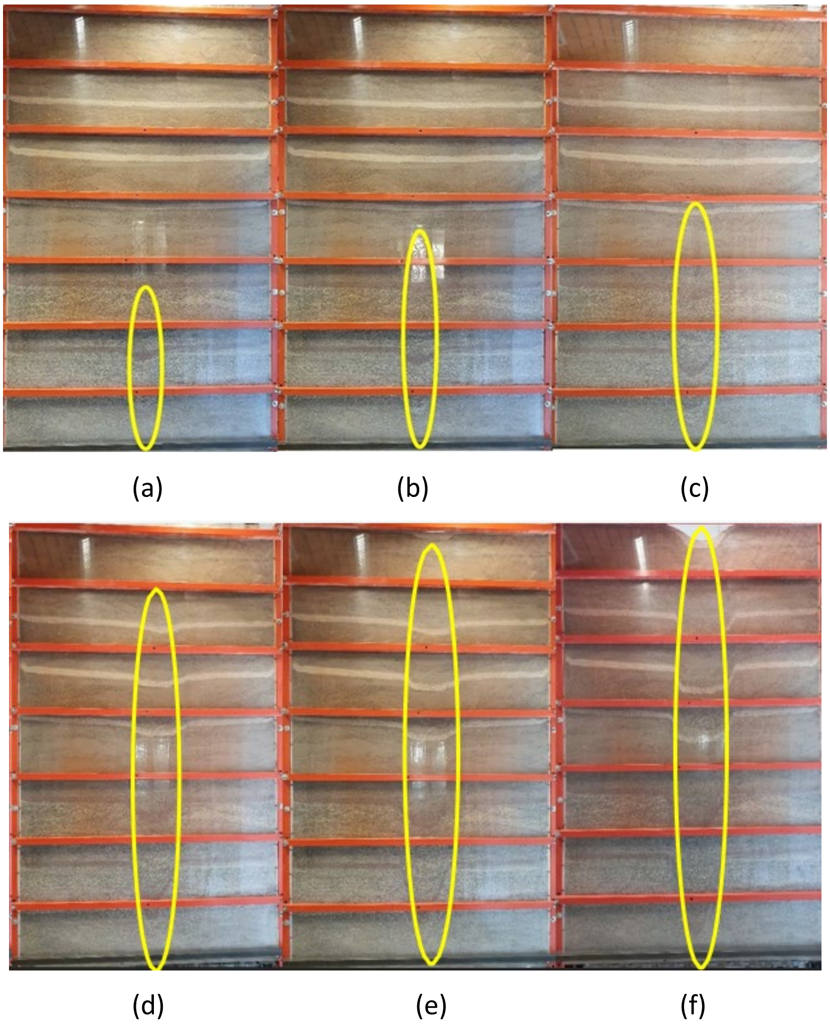


Figure 5 Profile view of the isolated movement zone at different draw stages. (a) 5.1 kg of mass draw; (b) 10.2 kg of mass draw; (c) 13.5 kg of mass draw; (d) 20.4 kg of mass draw; (e) 25.5 kg of mass draw; (f) 35.7 kg of mass draw

In this experiment, material is extracted from a single drawpoint located at the centre of the model. The stress results are presented in Figure 6. During the experiment, the IMZ diameter reached 40 m (mine scale) after 27 kg of material had been extracted (indicated in Figure 6 bottom). At this stage, load cells 1 and 2 were located beneath the flow shadow zone. Subsequently, the IMZ diameter increased to 36 cm after 24 kg of extracted material, covering load cell 1, which is located 10 cm from the active drawpoint. A decrease in vertical stress was observed in the load cells closest to the drawpoint (cells 1 and 2).

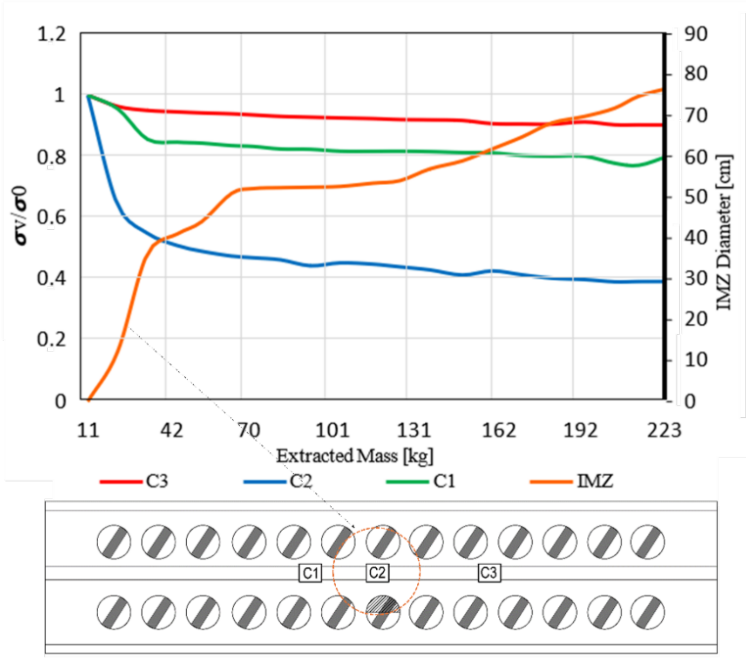


Figure 6 Vertical stresses (σv) measured on the crown pillar during experiment 1. Here σ0 is the initial vertical stress, before draw and IMZ is the isolated movement zone

It is well known that granular flow induces higher porosity near the drawpoint (Firouzabadi et al. 2023; Pierce 2010). Within the extraction zone, bulk density decreases due to this increase in porosity. Consequently, higher porosity reduces the number of contact points available for stress transmission within the granular material, promoting the transfer of stresses towards more compacted regions, which in this case correspond to zones where no extraction occurs. In the non-extraction zone (cell 3), no significant variation was observed compared with cells located under the extraction zone.

3.2 Experiment 2: multiple draw

The objective of this experiment was to quantify the vertical stresses induced on the crown pillar at the production level under an interactive draw configuration in which all drawpoints within the footprint extract material almost simultaneously over a given period. The location of the load cells used in this experiment is shown in the bottom of Figure 7.

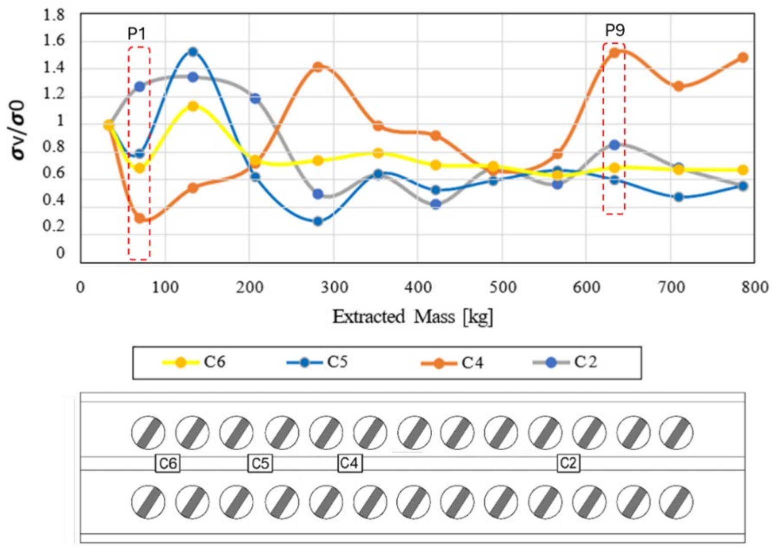


Figure 7 Vertical stresses during extraction in experiment 2 and location of load cells (bottom)

In Figure 7 it can be observed that once extraction begins in period 1 (P1), load cells 4, 5 and 6 are located beneath a relatively uniform extraction zone; consequently, they record lower stress values compared to the initial state during the first extraction period. A more detailed analysis for each extraction period is required to better understand the behaviour of induced stresses at the production level. For this reason, the extracted mass at each drawpoint was tracked over time to identify potential over-draw conditions that could explain fluctuations in the induced vertical stress values (Figure 8).

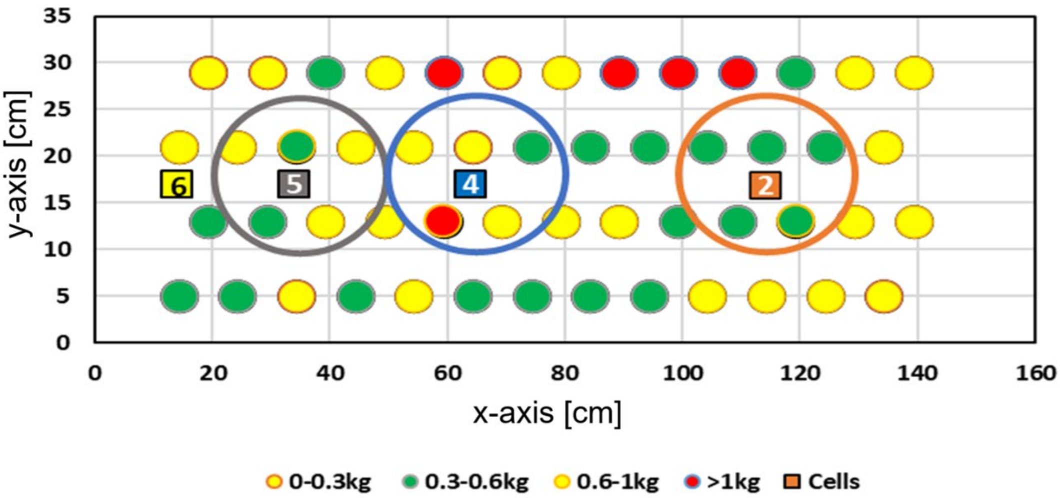


Figure 8 Extracted mass at each drawpoint during period 1 of experiment 2

In particular, for load cell 4, neighbouring drawpoints exhibit uneven extraction, with the highlighted red drawpoint in Figure 8 exceeding 1 kg, while adjacent drawpoints extracted less than 1 kg, including one below 0.6 kg. This can be associated with a local over-extraction zone during this period. When compared with the load cell 4 records for period 1 in Figure 7, a significant decrease in induced stress can be observed. In contrast, based on the colour scale in Figure 8, load cell 2 is located beneath a zone with lower extraction compared to adjacent areas, which explains the increase in induced stress relative to the initial value (Figure 7). This behaviour persists in subsequent extraction periods.

Additionally, Figure 9 shows that during period 9 (with a total of 625 kg extracted), load cell 4 exhibits a sudden increase in stress. This is attributed to its location within a zone of relatively lower extraction, on the order of 1 to 1.3 kg per drawpoint, which leads to an increase in the recorded induced stresses (Figure 7). Meanwhile, load cells 5 and 6 exhibit similar extraction levels, which is also reflected in comparable vertical stress values during this period.

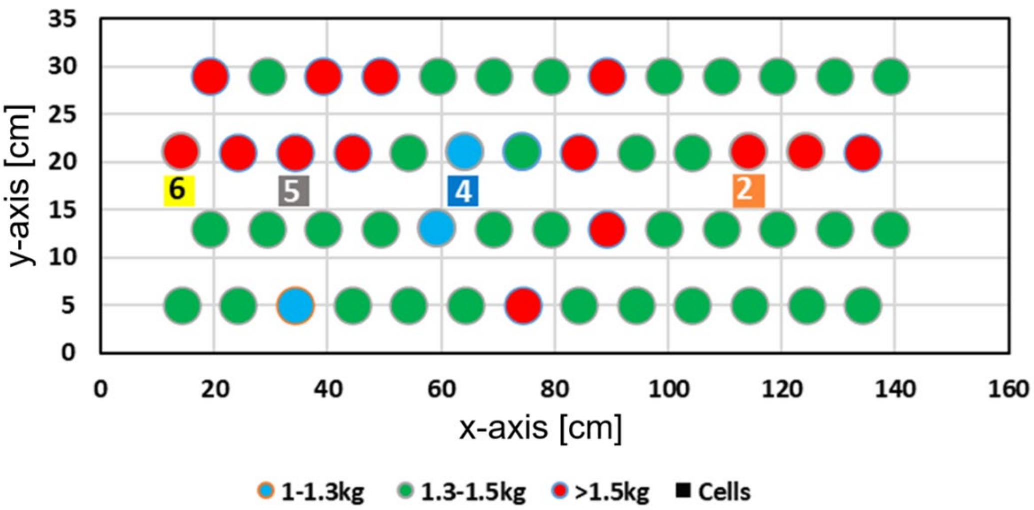


Figure 9 Extracted mass at each drawpoint during period 9 of experiment 2

These experiments demonstrate that stresses are redistributed from zones with higher extraction to zones with lower extraction. In other words, zones that were previously in motion may experience stress concentration if extraction decreases or ceases. Furthermore, uneven extraction leads to significant variations in induced stresses on the crown pillar. When a low-extraction zone is adjacent to a high-extraction zone, induced stresses can reach values significantly higher than the initial stress. Conversely, in zones with lower extraction, induced stresses can reach up to 1.6 times (Figure 7) the initial stress.

4 Conclusion

The measurement of stresses on the crown pillar under isolated draw conditions (experiment 1) confirms trends reported in previous studies. In particular, induced stresses decrease when measurement points (load cells) are located within movement zones, with the magnitude of the reduction being proportional to the distance from the drawpoint within the solated movement zone. Conversely, induced stresses increase when measurement points are located outside the movement zones. In the vicinity of an isolated drawpoint, the induced vertical stress acting on the crown pillar at the production level decreases to approximately 40% of the initial stress (cell 2 in Figure 6) and may be further reduced due to overall system extraction. In contrast, the results from experiment 2 indicate that under multiple draw conditions, variations in extraction (e.g. ± 2,500 t) are reflected in the induced stresses within the broken material over the crown pillar. This occurs even under conditions where the entire column is within the extraction zone, with stress values exceeding the initial stress. Furthermore, in stagnant zones (i.e. without extraction), induced stresses can reach up to 1.6 times the initial stress. These findings highlight the importance of draw control strategies, such as the uniformity index, in managing stress redistribution and ensuring the stability of the production level in deep caving operations.

Acknowledgement

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