

# Modelling considerations for cave compaction at New Afton Mine

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## Abstract

*New Afton is a block caving mine located 10 km outside of Kamloops, British Columbia, Canada. The mine operates two lifts, Lift 1 and B3, with two separate caves on Lift 1, the West Cave (WC) and the East Cave (EC). Lift 1 and B3 production levels are located approximately 600 m and 760 m below the ground surface. New Afton has a unique combination of geometric geotechnical conditions when compared to other cave mines, including: 1) a narrow and long footprint; 2) faulted and poor ground areas; and 3) a high horizontal induced stress environment.*

*During mining of the EC, where a majority of the poor rock mass conditions exist, after the cave was propagated through to surface, local areas of the footprint experienced severe damage and high tunnel convergence, which led to some areas being difficult to access and routinely mine. Because of this, the caved and fragmented material located on top of these drawpoints has experienced a high degree of caved rock compaction over time.*

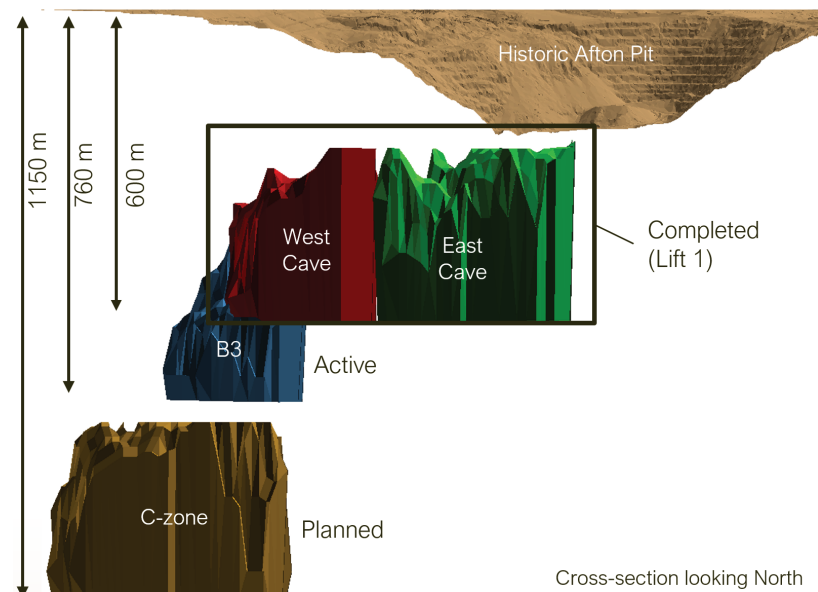
*New Afton was able to successfully rehabilitate much of these areas while observing compacted cave material, but in addition, a Front Cave Recovery Level (FC) was designed 20 m below a section of the EC production level with the purpose of mining the reserves below and recovering supplemental reserves left by the drawpoints.*

*Cave propagation within compacted cave material requires additional consideration when being used in modelling. A methodology to consider compaction within the EC was proposed using the IMASS model. Assuming two different degrees of compaction for the pre-existing EC, the FC was then assessed with a coupled modelling approach using FLAC3D and REBOP to simulate both the draw/flow and caving propagation to determine abutment stresses and cave loads induced on the production level as material was drawn. It was found that having different degrees of compaction significantly affected the predicted caving rate and cave geometry, affecting ultimate recovery.*

**Keywords:** *numerical modelling, cave compaction, cave propagation, Front Cave, recovery level*

## 1 Background

New Afton is a block caving mine located 10 km outside of Kamloops, British Columbia, Canada. The mine was developed between 2007 and 2012, and mill production commenced in 2012. A schematic view of the New Afton Mine is shown in Figure 1. Currently, there is only one cave in operation, the B3 cave located beneath and to the west of the Afton pit (~1,150 m below the surface). The East Cave (EC) is separated from the West Cave (WC) by a waste pillar 50 m to 60 m thick. The EC layout is 110 m to 130 m wide by 310 m long.



**Figure 1** New Afton Mine layout

Laubscher et al. (2017) discussed cave compaction as one of the several unanswered questions in cave mining. In the actual cave mining process, sustained draw at any drawpoint is not possible, and there are times when drawpoints are not drawn, sometimes for extended periods. This can lead to time-dependent compaction, particularly in more altered ores and faulted areas with high content of clay.

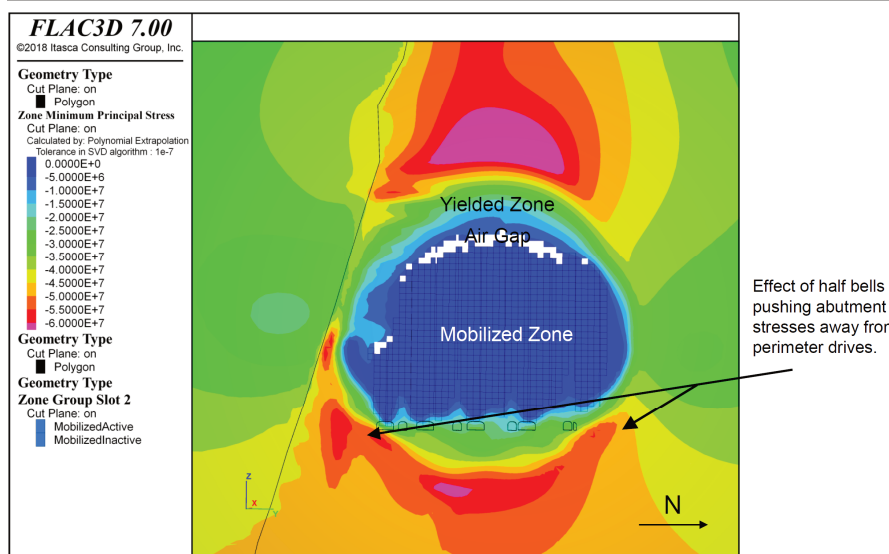
The time-dependent compaction of cave rock following cessation of mining has a number of different practical consequences as explained by Kwok & Pierce (2011):

- It can lead to secondary fragmentation and reduction in cave rock porosity, which both affect gravity flow. This is the most relevant consequence in this study. It also could impact the distribution of stresses within the cave and the potential transfer of high stresses to the Extraction Level.
- It can result in time-dependent cave growth, as it leads to a drop in confinement in the overlying rock mass and subsequent advance of the yielded zone. Stewart et al. (1984) described that during a shut-down at Henderson Mine in 1982 and 1983, the crater continued to expand in volume, possibly as a result of the compaction of caved material under continued static loading.

## 2 Cave compaction at New Afton

In a caving operation, as the cave propagates, stresses redistribute to develop a 'yielded bowl' underneath the production level as shown in Figure 2. The yielded bowl is a portion of the rock mass that has reached its peak strength and undergone plastic strain to a level that it is not capable of carrying high stresses anymore. A narrow layout, like the EC, results in a smaller, shallower yielded bowl relative to the footprint closer to the production level, while in a wider layout the yielded bowl is larger and deeper relative to the footprint width; hence, the production level is less exposed to high induced stresses and further potential damage. New Afton developed a single-sided drawbell located on the boundaries of the cave to protect production drives from high abutment stresses, providing stress shading to the perimeter strikedrive and drawpoints, effectively increasing the size and depth of the yielded bowl.

## Section N-S showing S1 [MPa]



**Figure 2** Example of yielded bowl and influence from footprint width, affecting the change in depth, with higher stresses distribution around the perimeter of the footprint (Fuenzalida & Pierce 2019)

Certain areas of the EC did not have single-sided drawpoints or alternatively, they were not drawn, allowing higher induced stresses to develop local to the production level. This in combination with major faulting, poor ground conditions, and non-uniform draw strategies lead to areas of high convergence, resulting in production challenges and re-development of certain drawpoints. These areas remained inaccessible until re-development was completed. Once the drawpoint was accessible for production, observable compaction of the draw column at the drawpoint was observed, requiring additional efforts to successfully start production. Figure 3 shows photos of a compacted drawpoint in the EC footprint.

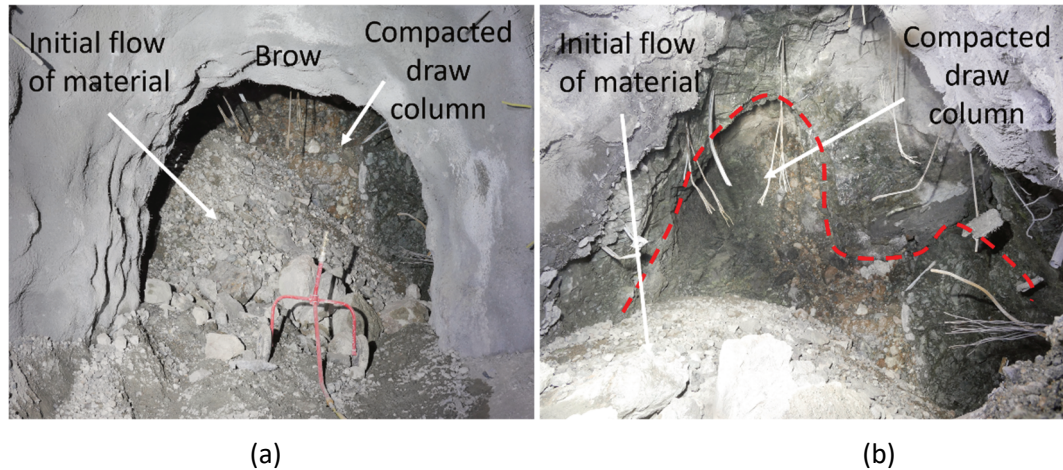


**Figure 3** (a) Observed compaction beyond the brow, within the drawpoint, no material flowing, dashed lines representing converged walls within the drawpoint (originally 4.2 m wide); (b) Sprayer used to assist with compaction and re-establish the flow of the ore column, allowing the material to start flowing (Kamp 2022)

Different degrees of compaction have been observed (Figure 4a), resulting in variable time to re-establish material flow from a drawpoint. The areas requiring additional efforts have been typically associated with higher cumulative displacements due to convergence, clay or alteration of the rock mass, faults, and locality to induced stresses (typically located within the perimeter of the cave). Some investigation efforts based on drilling feed pressure have been completed to understand the level of compaction. These sample drilling data are located near the drawpoint brow with the primary purpose of determining an ideal location to re-install steelsets. Drilling completed within the compacted material indicate that the highest compaction is present



from the production level to the top of the previously blasted undercut level where the feed pressure required is reduced. However, more work needs to be completed to better understand this. Once production is re-established, it is observed that the draw column geometry shape has significantly changed from the initial drawbell blast design, resulting in a much narrower and local area of draw as shown in Figure 4b. In some cases, after these areas have been re-established, the narrow column can be observed, resulting in being more sensitive to oversize hang-ups due to the smaller geometry (Figure 5).



**Figure 4** (a) Observed compaction beyond the brow, within the drawpoint, some material starting to flow on the left, water sprayer pictured; (b) View into the same drawpoint showing formation of a narrow draw column, red dashed line representing converged walls about 1 m apart



**Figure 5** A different location showing the narrow ~0.7 m diameter draw column in a drawpoint due to compaction after draw has been established and is not flowing due to oversize

Beneath the EC, an area was identified for Front Cave mining with the purpose of mining an area 20 m below the EC and additionally recovering remaining ore from closed drawpoints above the EC production level. To assist with understanding the draw prior to mining the Front Cave, a numerical assessment was carried out to better understand the potential impact of the EC compaction.



### 3 Simulation of cave compaction

#### 3.1 Expected behaviour within the caved column

Because the lateral boundaries of a cave are generally rough in nature, arching would be expected to occur between this volume and the surrounding uncaved ground. To ignore arching in this case would result in an unrealistically high initial cave stress and correspondingly high stagnant zone stresses.

Lorig (2000) demonstrated, through a combination of limit equilibrium and numerical modelling, that the initial vertical stresses at the base of a cave or draw area might be significantly lower than the total weight of caved material in the overlying column. The amount of arching depends on the hydraulic radius of the cave, the height of the cave and the frictional resistance at the cave periphery, as suggested by the bin theory of Janssen (1895).

Stress arching was encouraged in Castro's (2006) physical model, resulting in initial vertical stresses that were only 70% of the overburden weight. Pierce (2010), using a horizontal-to-vertical stress ratio of 0.36, tested the bin theory of Janssen with Castro's results, concluding that Janssen's equation may provide a reasonable starting point for estimating the initial (average) stresses inside the cave.

This study aims to capture the arching behaviour, emergent vertical stresses and a target bulking factor representing cave compaction.

#### 3.2 Methodology

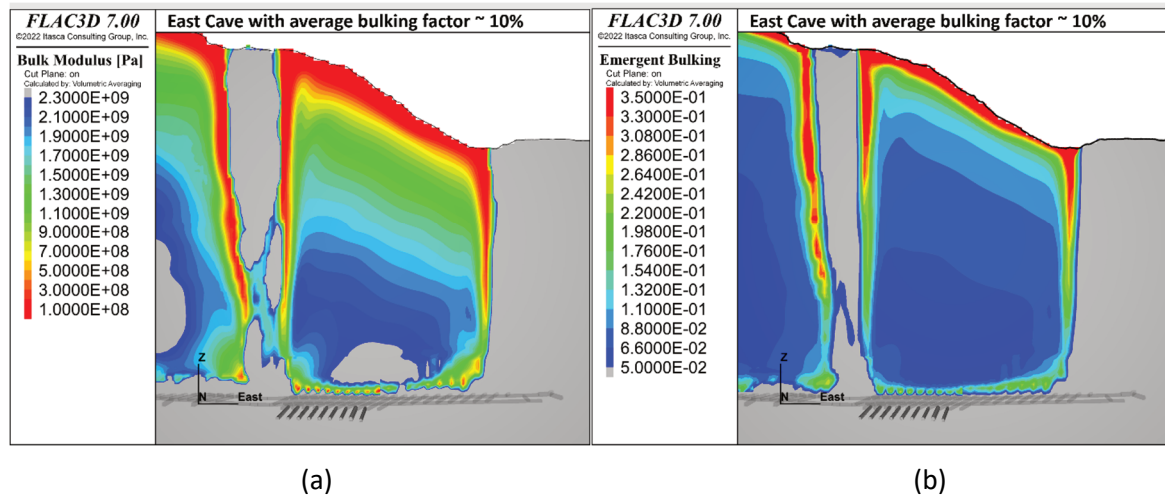
*FLAC3D* (Itasca Consulting Group 2019), a finite difference code, can be used to effectively simulate the arching behaviour inside a cave, and the non-linear vertical stress variation along the width can be identified. In this study, this is achieved by initialising the material inside the cave as broken rock (to its maximum porosity at an ultimate residual strength) as well as the stresses, and then letting the broken rock sit under gravity. Compaction is considered by repeating this process of removing stresses until reaching a target bulking factor within the cave. The simulation of this compaction is possible due to the use of the *IMASS* model (Ghazvinian et al. 2020), which includes two softening modes in the post-peak behaviour. The first, defining the decay from peak to post-peak strength, is controlled by accumulated plastic shear strain. It is assumed that at this stage (post-peak), the rock mass has lost all its cohesion, but there is a high degree of interlock (negligible bulking). The second softening stage, from post-peak strength to ultimate strength, is controlled by accumulated volumetric strain increment (bulking). At the ultimate strength, the rock mass has reached its maximum porosity and it can't continue dilating. By fitting a Hoek–Brown envelope to the Barton failure criterion for rockfill, *IMASS* relates the porosity of the rock mass with its strength. Given that cave compaction will result in a reduction of porosity, a hardening behaviour is expected. This will also provide the possibility for the rock mass to carry more stresses.

#### 3.3 East Cave example

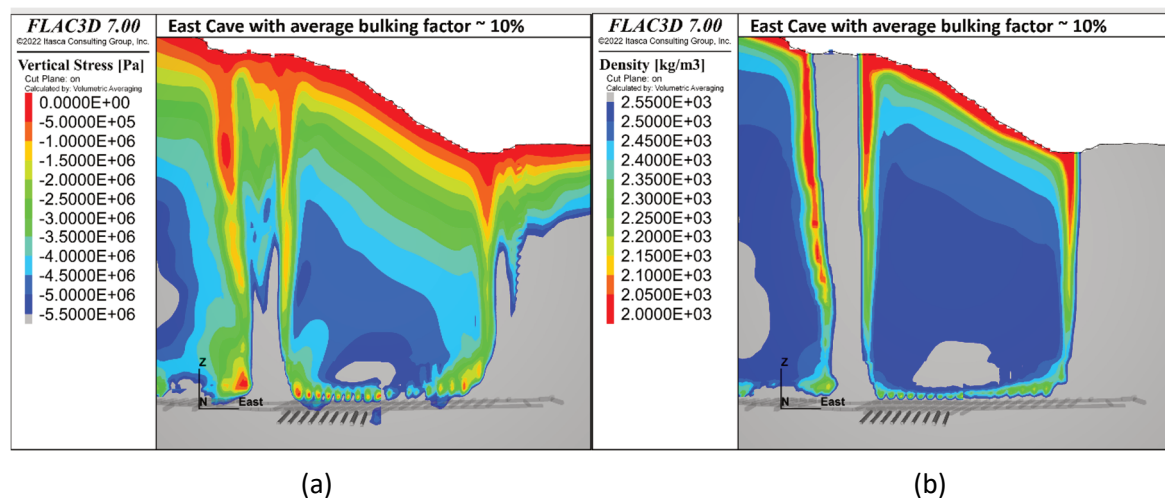
As discussed previously, due to different factors such as time, lithology, alteration, moisture, and clay content in faulted areas, the EC showed variable signs of compaction to an unknown degree. In order to study the Front Cave level, the East and West caves were initialised as a uniform material using an average strength from the initial lithologies. This was made to void any unrealistic behaviour for the presence of faults within the caved material. Then, following the methodology described previously, the old caves were initialised until an average bulking factor around 10% was achieved within the column. If no compaction is considered, then the average bulking factor would be around 40% in this case (with a maximum porosity of 30%). Figure 6 shows the resultant distribution of bulk modulus (a) and bulking factor (b) in the column, and Figure 7 shows the resultant vertical stress (a) and emergent density (b). The arching effect and the non-linear variation can be observed. The compaction of the material is higher in the bottom central area of the column as expected, while the boundaries of the cavities don't show significant compaction as the Janssen theory predicts. The resultant vertical stresses in the most compacted area of the EC (bottom central part) are around 75% of the

overburden weight with a horizontal-to-vertical stress ratio around 0.3 (and an average of 0.39 for the entire column).

Note that this methodology does not have a time-dependant component to estimate the degree of compaction of a cave over time. This methodology aims to reproduce the mechanical behaviours given a target degree of compaction, in this case a bulking factor of 10%.



**Figure 6** East–west cross-section showing East Cave compaction. (a) Emergent Bulk modulus in Pa; (b) Bulking factor



**Figure 7** East–west cross-section showing East Cave compaction. (a) Vertical stresses in Pa; (b) Emergent density in kg/m<sup>3</sup>

## 4 Effect of cave compaction in cave propagation

### 4.1 Numerical model

To support cave mining at New Afton Mine, a hybrid *FLAC3D-REBOP* modelling approach has been used (Fuenzalida et al. 2018). This hybrid approach allows prediction of the limits of the geomechanical zones defining the cave as a function of production. The results of the model can be used to derive estimates of 1) caveability and caving rate; 2) abutment stresses and cave loads; 3) recovery and dilution entry; 4) fragmentation; and 5) breakthrough timing and subsidence.

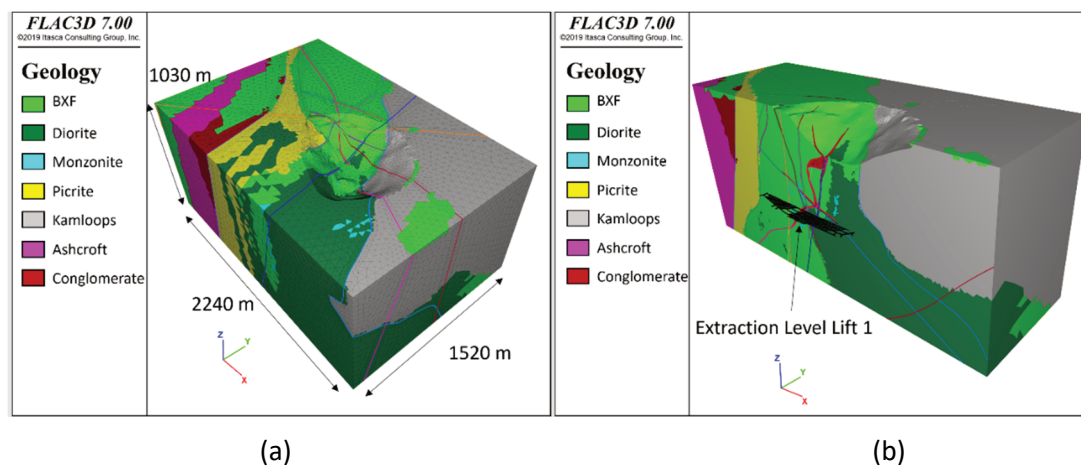
The approach simulates the caving process by explicitly modelling each isolated movement zone derived from *REBOP* (Pierce 2010) into *FLAC3D* to determine the yielded zone and cave-back associated with mass

drawn. After one cycle of extraction, *REBOP* informs the location of the movement zones and the presence of air, if it exists, to the continuum *FLAC3D* model. *FLAC3D* solves stresses associated with the presence of these zones and estimates the yielded zone surrounding the cave. *FLAC3D* informs *REBOP* which zones (initially inactive) could now be mobilised. The procedure is repeated until the draw schedule, used as an input in *REBOP*, is finished.

The effect of the EC compaction in the Front Cave propagation was assessed by simulating a case without compaction, assuming that the rock mass is fully broken, and it has reached its maximum porosity (~30%) equivalent to a bulking factor of 40%. Also, a compacted case is simulated assuming a target average bulking factor of 10% within the column following the methodology previously described using the *IMASS* constitutive model.

## 4.2 Geotechnical domains

The geotechnical domains at New Afton have been defined by lithological boundaries. Seven generalised lithology types can be found in the area of the EC, which are BXF, Diorite, Monzonite, Picrite, Conglomerate, Kamloops and Ashcroft, as shown in Figure 8. The faults present in New Afton are also considered as a geotechnical domain due to their strong influence in the stability of the footprint and cave propagation.



**Figure 8** Geotechnical domains included in the *FLAC3D* model. (a) ISO-view of the *FLAC3D* model; (b) ISO-view showing an east-west cross-section along Lift 1

## 4.3 In situ stress

A re-assessment of overcoring and Sigma measurements conducted by Agapito Associates Inc. (2018) at New Afton Mine suggests that the major principal stress is generally trending N-S and dipping sub-horizontally with the minor principal stress assumed as the overburden stress. The horizontal-to-vertical stress ratio for the major principal stress (N-S) is approximately 1.7, while the horizontal-to-vertical stress ratio for the intermediate principal stress (E-W) is 1.1.

## 4.4 Rock mass properties

As introduced by Pierce (2013), a numerical model that represents the caving process must account for the progressive failure and disintegration of the rock mass from the intact/jointed elastic condition to a fully broken material. In this complex process, creation of the cave results in:

- Deformation and stress redistribution of the rock mass above the undercut.
- Failure of the rock mass in advance of the cave, with an associated progressive reduction in strength from peak to residual levels.
- Dilation, bulking, fragmentation and mobilisation of the caved material.



This overall process of loading the rock mass to its peak strength, followed by a post-peak reduction in strength to some residual level with increasing strain, is often termed a strain softening process and is the result of strain-dependent material properties. The *IMASS* constitutive model was used in this study to capture these complex mechanisms.

The rock mass properties used and required by *IMASS* are listed in Table 1, with ongoing assessment of rock mass characterisation at the mine site. Note that the intact rock Young's moduli listed in Table 1 are later scaled to rock mass modulus using the approach developed by Hoek & Diederichs (2006). The Poisson's ratio is obtained through GSI using the equation developed by Lorig & Varona (2013).

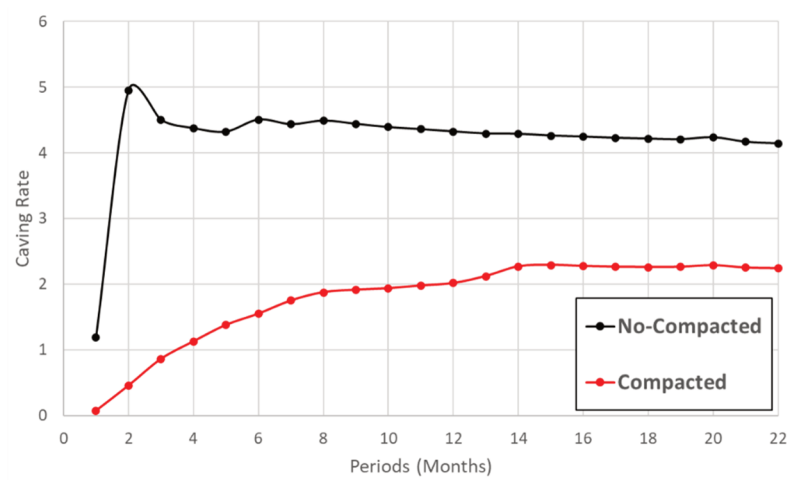
**Table 1 Peak strength rock mass properties used in this study (New Afton 2016)**

| Domain       | Density (kg/m <sup>3</sup> ) | GSI | UCS (MPa) | m <sub>i</sub> | E <sub>i</sub> (GPa) |
|--------------|------------------------------|-----|-----------|----------------|----------------------|
| Picrite      | 2,700                        | 53  | 56        | 15             | 50                   |
| Diorite      | 2,700                        | 45  | 67        | 20             | 36                   |
| Conglomerate | 2,700                        | 44  | 48        | 15             | 24                   |
| BXF          | 2,700                        | 60  | 51        | 20             | 45                   |
| Kamloops     | 2,700                        | 44  | 48        | 15             | 24                   |
| Monzonite    | 2,700                        | 55  | 62        | 20             | 47                   |
| Ashcroft     | 2,700                        | 45  | 67        | 20             | 36                   |
| Faults       | 2,700                        | 44  | 24        | 15             | 24                   |

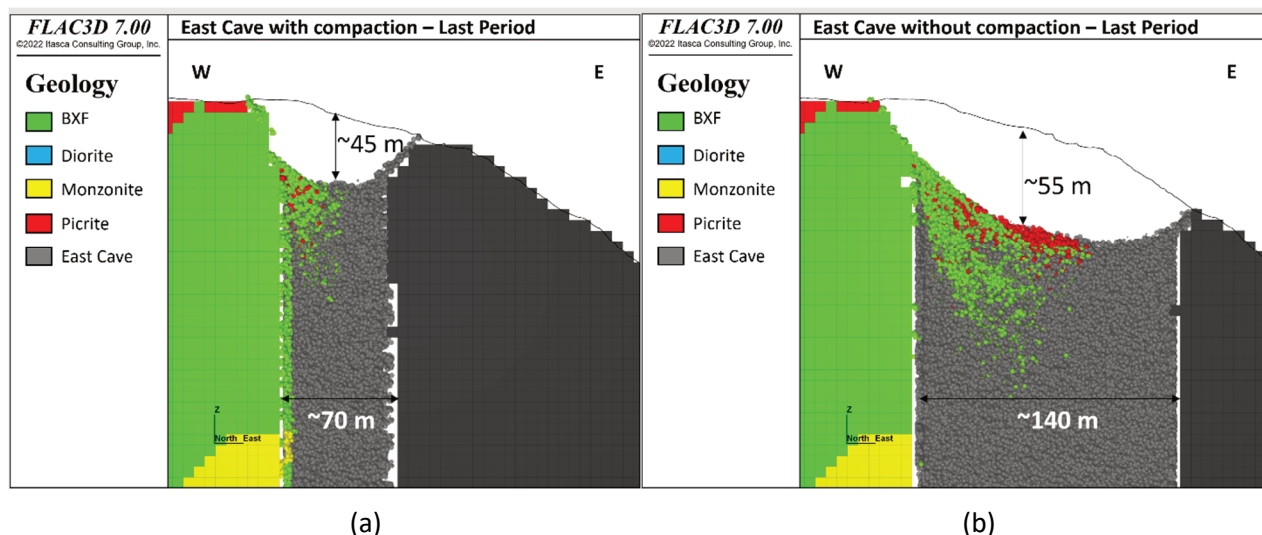
## 4.5 Results

Figure 9 shows the effect of compaction in terms of average caving rate. The compacted case (red line) shows lower caving rates. The case without compaction (black line) shows higher caving rates because the column above is able to flow from the beginning of active mining. The first period shows a low caving rate for both cases because the Front Cave is initially mining ore below (through intact material) the EC prior to recovery mining the EC broken material.

The cave compaction impacting the cave propagation will also result in different surface subsidence. As shown in Figure 10, the resultant crater geometry can be different if compaction is assumed for the EC. In this case, the horizontal extension of the crater considering compaction is half (~70 m) of the case without compaction (~140 m), which is also 10 m deeper.

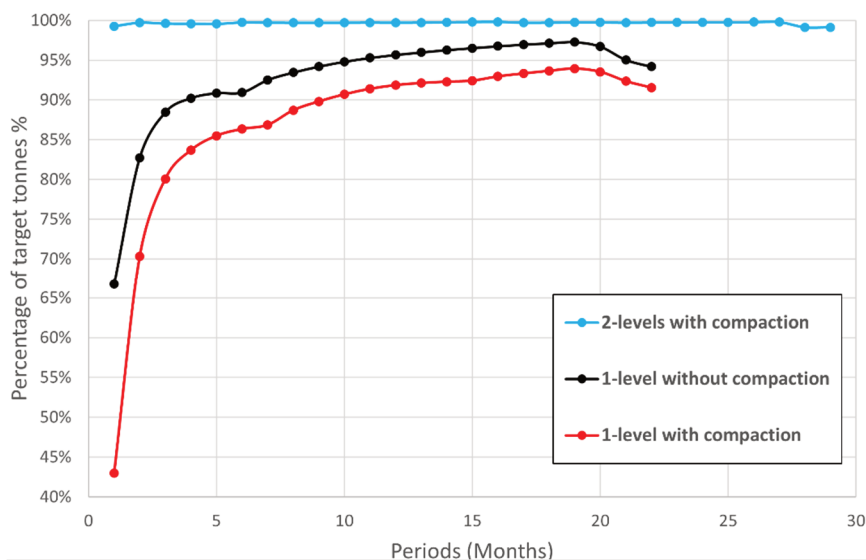


**Figure 9 Caving rate comparison between cases with and without compaction**



**Figure 10 East–west cross-section showing geology closer to the surface. (a) Resultant crater of the case with compaction; (b) Resultant crater of the case without compaction**

The numerical assessment also showed that the EC compaction could have an impact on productivity in terms of percentage of target tonnes (defined by the draw schedule) effectively drawn as shown in Figure 11. To understand the performance of a two-level Front Cave below the EC, scenarios were simulated for a single- and two-level design assuming compacted EC material. As shown in Figure 11, the percentage of target tonnes effectively drawn from the two-level design is notably higher than that from the one-level design. This is because by utilising two levels, the first (upper) level acts as an undercut level to establish an appropriate hydraulic radius (in this case site observations indicate a critical hydraulic radius of 10 m), inducing stresses, weakening and mobilising the compacted rock mass located above the EC, allowing the second level to produce the majority tonnes of ore. If a block cave method was chosen instead, a smooth ramp-up strategy should be considered to reach the critical hydraulic radius before reaching regime levels of draw.



**Figure 11 Results of ore recovery for three analysed cases. One level without compaction (black), one level with compaction (red), and two levels with compaction (cyan)**

## 5 Conclusion

A numerical methodology modelling has been proposed to consider cave compaction by using the *IMASS* model and reaching a target degree of compaction. A hybrid *FLAC3D-REBOP* approach has been applied to study the impact of the EC compaction on the cave propagation of the Front Cave at New Afton Mine. Cases with and without compaction were simulated in conjunction with the recovery cave mining. The modelled results suggest that the EC compaction can have a significant impact on the cave propagation of the Front Cave (in terms of caving rate and subsidence) and on productivity when considering a one-level design. A two-level design was found to mitigate the potential caveability and productivity risks associated with cave compaction.

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