

Progress towards volumetric monitoring of cave mine propagation with novel quantum absolute gravity methods

L. R. McCalman^a, P. B. Wigley^a, K. S. Hardman^a, C. M. Freier^a, M. D. Flynn^b, L. A. Snyman^b
and S. Z. Pieczonka^a

^a*Nomad Atomics Pty Ltd, Melbourne, Australia*

^b*Northparkes Operations, Parkes, Australia*

ABSTRACT

Cave mining, a critical sector in the mining industry, faces significant challenges due to its dynamic and complex nature. Recent advancements in geophysical techniques have opened new avenues for monitoring subsurface changes in these mining environments. However existing methods do not provide sufficient spatial or temporal resolution to allow for accurate real-time modelling of the cave.

Changes in cave geometry during all phases of the mine life cycle including tunnelling, fracturing, cave evolution, and extraction are accompanied by changes in mass. Importantly, the intra-cave structure which is invisible to mine operators such as cave back, air gap and muck-pile geometry, all exhibit contrasting densities. Measurements of the gravitational acceleration are conducive to sensing these mass changes. However, traditional gravity surveys utilizing relative gravity meters are hindered in underground environments such as cave mines, due to instrument drift and error propagation. These issues are amplified in underground scenarios where it is difficult to recalibrate or correct the measurements, leading to poor resolution and a lack of repeatability where time-lapse (monitoring) solutions are required.

Quantum absolute gravimeters could provide a solution to these problems, by providing absolute gravity measurements, i.e. not relative to any other measurement in space or time. A quantum gravimeter measures the gravitational acceleration by interrogating atoms under the free fall of gravity and observing their interference patterns. Such a sensor measures the absolute value of gravity with each measurement and is not susceptible to the drift and error issues plagued by gravimeters relying on mechanical parts, making the measurements repeatable over time. Absolute measurements of gravity could provide a pathway to characterising the inner cave structures, as well as constrain the total mass change within the cave.

This study investigates the potential for timelapse absolute gravity methods to provide 3-dimensional tracking of cave dynamics. Using real-world density block models, we first simulate the gravity signal generated by the changing resource in a progressing block cave as it would be measured from surveys completed along the extraction drives. We demonstrate the first step toward inverting this gravity signal to identify features of the cave, such as the muck pile, airgap, and cave back. This work could pave the way for underground mines to harness gravity surveys to produce more accurate models of cave progression, and ultimately improve real-time operational insight into the caving process.

1 INTRODUCTION

Characterising the structure of block caves is critical to ensuring safe and efficient extraction of resources mined. Identifying large air gaps

below the cave top is particularly important, as these gaps create the potential for sudden cave-ins causing dangerous air blast events (Flores-Gonzalez, 2019).

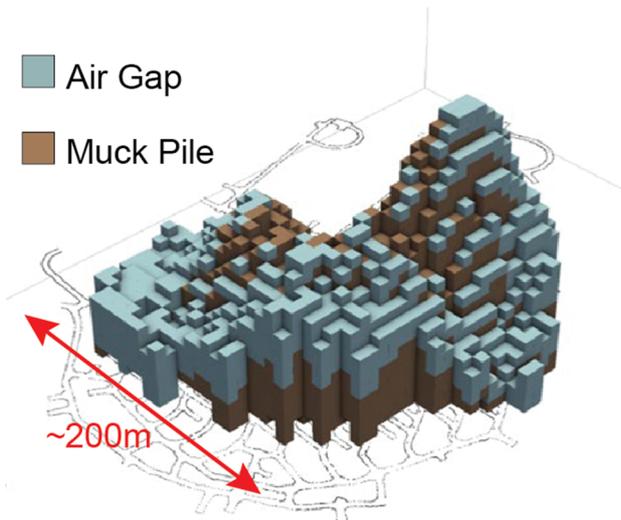


Figure 1 Cave geometry predicted by inversion model. Brown voxels represent muck pile and blue voxels represent air.

Gravity observations are a promising source of additional data to aid this effort. Conducting underground gravity surveys in the cave's extraction drives would enable the use of geophysical inversion as a modelling approach to complement existing methods. Gravity inversion is a computational and statistical modelling technique that uses sensitive measurements of gravity to infer the nearby distribution of matter and is a standard technique in exploration (Kearey, Brooks, & Hill, 2002).

However, gravity surveying of block caves has been practically infeasible for two main reasons: firstly, the lack of surface access due to potential subsidence prevents gravity measurements above the cave. Secondly, the need to repeatedly calibrate traditional commercially available gravimeters against absolute reference measurements (Ménoret, et al., 2018) complicates their use underground, especially when trying to capture changes over time.

The fundamental difference between a quantum absolute gravimeter and a traditional field gravimeter such as a Scintrex® CG-6, is that the quantum sensor uses atoms to measure gravity, instead of mechanical parts like a spring or weighted mass.

Quantum absolute gravimeters measure gravitational acceleration by observing the free

fall of super-cooled atoms in a chamber under the force of gravity. The atom clouds are controlled and measured by extremely accurate laser beams. Because the atoms are contained within the chamber and calibration is dependent only on the laser frequencies, the instruments are insensitive to environmental influences such as temperature and air pressure fluctuations and magnetic fields (McGuirk, Foster, Fixler, Snadden, & Kasevich, 2002). The lack of mechanical parts such as springs and weights eliminate instrument drift and miscalibration. Although this technology has been continuously developed and improved upon over recent decades (Kasevich & Chu, 1991; Peters, Chung, & Chu, 2001), their use has been mainly confined to the laboratory due to their large size, weight, and dependence on carefully controlled laboratory conditions (Wu, et al., 2014). Two major obstructions then exist for underground measurements of gravity for their use in mining applications, i) absolute measurements are required to eliminate drift and error, ii) such absolute gravity measurements must be portable, mobile, and easy to deploy in underground environments.

The quantum absolute gravimeter discussed herein addresses these issues and makes underground gravity surveys practical. The two major advantages are its a) high accuracy and lack of drift, and b) compactness and portability, which allows for easy surveying within extraction drives. This sensor can be used for precise measurements of absolute gravity across multiple surveys taken as the cave evolves.

In this report, the gravity signals were simulated from realistic voxelised density models which represent the cave progression and changing geometries over time. These data were provided by mine operators and serve as the "true" models in this study, which we then compare to our inversion model results. Sensors were placed along the extraction drives, as would happen in the real-world survey scenario. A sensor spacing of 10-20m was chosen for this block cave by determining the minimum spatial density required to capture adequate detail while minimising survey duration. For the chosen survey scenario, an appropriate balance was arrived on using 20m station spacing along the

drives, which yields 110 total gravity observations along 11 drives, and an estimated 9 hours total survey time in the extraction drives.

Using this survey design, we performed a simulated gravity survey using two time-separated block models. The gravity data calculated from the geological models was then used to estimate the cave structure via in-house geophysical inversion processes (seen in Figure 1).

Combining the gravity survey data with other accessible data from the mine (such as extracted mass estimates, drill holes, and cave floor structure) yields an inversion result that shows a good qualitative match to the ground truth, showing similar topographic structure of the muckpile and surrounding airgap.

This represents the first steps in the development of techniques for gravity inversion in the context of underground mining and shows the feasibility of the method. Alongside these initial stage feasibility simulations, we have identified a number of avenues that may improve the performance of the inversions and produce more accurate structure estimates. These include incorporating additional available sensor data such as that from passive seismic arrays and adding geologically informed constraints on cave geometries.

2 FORWARD MODELLING

All modeling performed in this project is based around two 3D density models of a real-world underground block cave mine, provided by mine operators, at two timesteps, separated by approximately two years (Figure 2). These models take the form of 3D voxel grids of rock densities with a total of ($xx = 40$, $yy = 40$, $zz = 43$) voxels, each $20\text{m} \times 20\text{m} \times 20\text{m}$ in volume.

Using these models, we simulate surveys along the extraction drives, consistent with the proposed approach for the real surveys. By surveying directly below the resource, the changing mass can be directly measured via a gravity map. The proximity of the extraction level to the changing mass also maximises the gravity signal ensuring the highest signal-to-noise and therefore greatest level of insight.

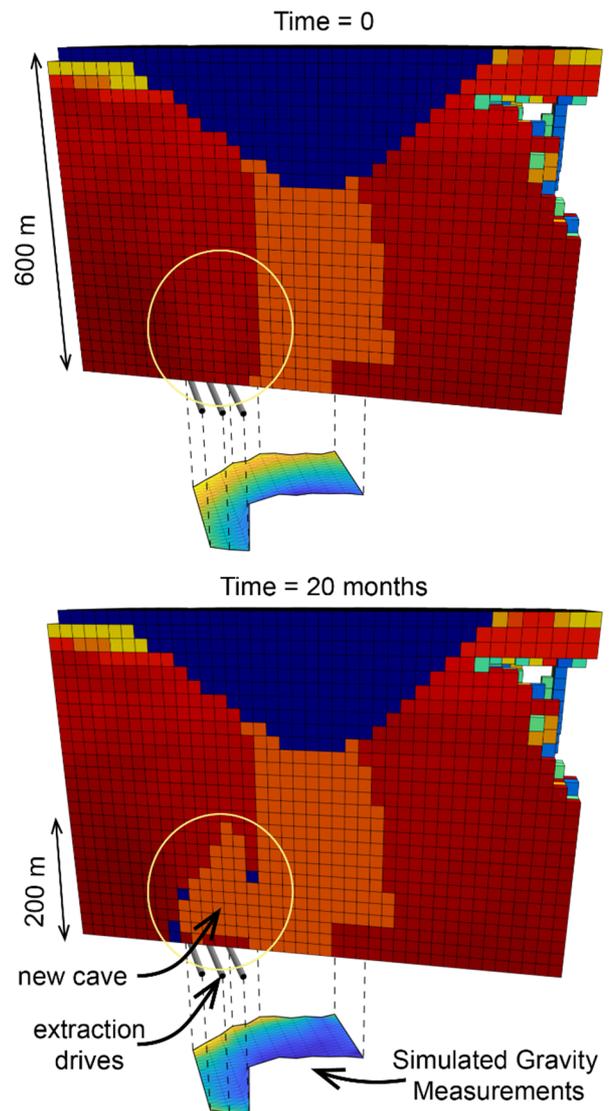


Figure 2 Cross-section view of the 2 ‘true’ voxel models showing the development of a new cave to the left of an existing completed cave. The voxels have been coloured to highlight variations in rock density.

Figure 3 illustrates these extraction drives, with survey lines indicated in red. The gravity signal will be measured at even spacings along these lines. Section 2.2 examines the ideal linear spacing of these survey points to balance observation detail with acquisition time.

2.1 Simulation of gravity observations

Gravity is linearly related to mass per unit volume (density), and the signal decays by the inverse square of the distance between the mass

element and the sensor. Here we have mass elements defined in cubic voxels of constant density, and we can simply integrate over the volume to sum each voxel's density contribution based on the voxel's separation from the sensor. An exact solution for the gravitational field of these is known in the literature: we use Bessel's method (Bessel, 1813) as implemented in (Fukushima, 2020).

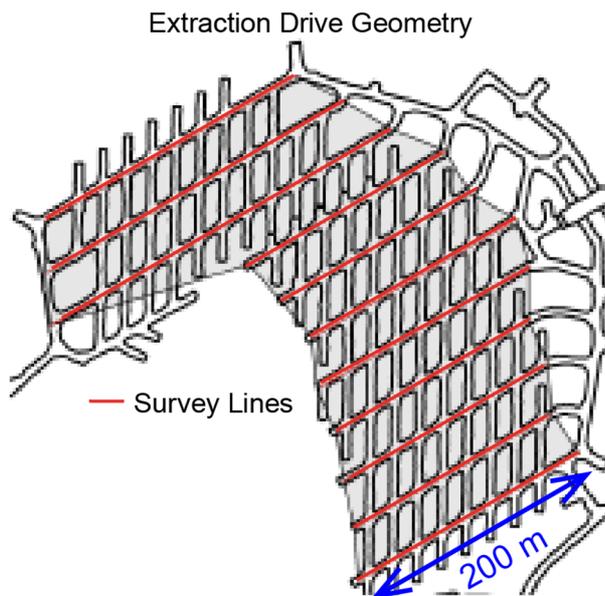


Figure 3 The extraction drives and surrounding tunnels. Red lines indicate the tunnels along which simulated gravity measurements are taken.

Using the difference in density per voxel between the two time-steps, we can simulate and observe the difference in the gravity signal that we would expect to see if we conducted a real gravity survey at Time 0 and again 20 months later (Figure 4). Here, the magnitude of the signal difference ranges between approximately 500 and 1700 μGals . The accuracy of the absolute gravimeter is 5 μGals , meaning that the sensor is plenty sensitive to the magnitude of the signals we see here from the changing densities during block cave evolution.

2.2 Gravity survey design

Gravity observations will only be useful in modelling changes to the block cave structure if those observations are sufficiently sensitive to detect the ensuing changes in the signal. The two

provided voxel models are enough to directly measure this change using forward modelling of differences and confirm the required sensitivity.

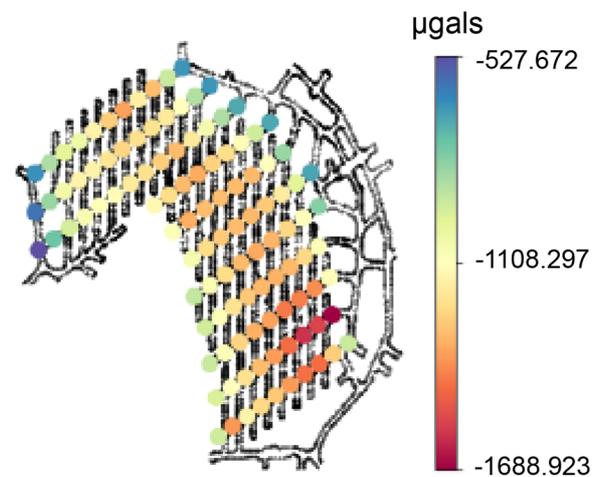


Figure 4 Simulated values of the difference between measurements of the zz -component of gravitational acceleration taken at the two timesteps ($T = 0$ months and $T = 20$ months).

2.2.1 Signal resolution

Based on the block models, the size of the signal difference arising from the cave propagation is on the order of mGal (10^{-5}m/s^2), which is three orders of magnitude larger than the target sensitivity of the absolute quantum gravimeter. This indicates that the signal would be sufficiently large to detect. Given that the two timesteps used in the simulation are approximately two years apart, and assuming a relatively constant rate of ore extraction over this time, we would expect to be able to see measurable changes in gravity over a fortnightly to monthly timescale suggesting an appropriate gravity survey cadence.

Further, more detailed, estimates of effective time resolution were completed by simulating single voxel shifts in cave heights with similar results.

2.2.2 Density of survey points

Determining the density of gravity survey points along the extraction drives is a balance between obtaining more data and increasing the time the survey takes.

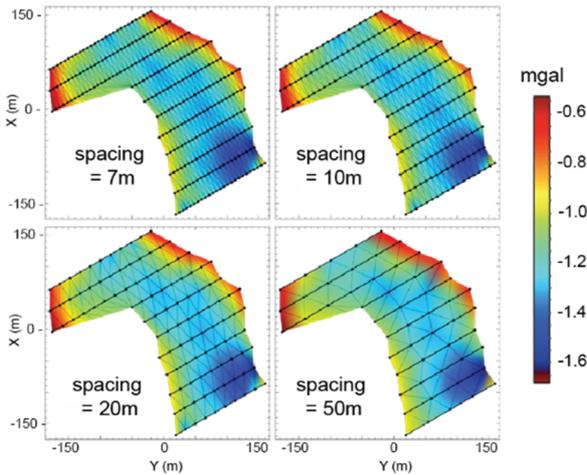


Figure 5 Interpolated gravity measurements taken at different spacing intervals.

The coarse voxelisation of the ground-truth creates artifacts in the gravity signal that provide a useful high-spatial-frequency signal to compare as the survey spacing is changed. At very low density (50m spacing), these artifacts are blurred to a point where the useful spatial information is lost. Given that each measurement is expected to take 5 minutes we estimated the total survey duration for different linear spacing in Table 1. A 10-20m survey spacing provides an optimum between spatial resolution and survey duration.

Table 1 Estimated survey times for various linear spacings

Linear Spacing (m)	Total Survey time in Extraction Drives (hours)
7	23
10	17
20	9
50	4.5

3 INVERSION

3.1 Methodology

Estimating the cave structure from gravity measurements taken in the extraction drives is an inversion problem. We first define a world model that can represent a variety of relevant

geological structures depending on the value of parameters input to the model. In the case of gravity inversion, this world model must ultimately specify how mass is distributed in the region under study, or equivalently, the density distribution over the model volume. This density distribution is sufficient to estimate the gravitational field strength at any point in space. The general approach to solving inversion problems is to find parameters of a world model that generate gravity readings similar to those that were actually observed.

Gravity inversions are challenging for a number of reasons:

- Many different distributions of mass (i.e. different geological structures) will produce the same gravity measurements (non-uniqueness).
- Mass distributions in real systems such as block caves are geometrically complex, and choices must be made on how to represent them with a set of parameters.
- Exhaustively searching for world model parameters that produce a known set of gravity observations is computationally intractable for world models with even 10's of parameters. Fortunately, the general structure of block caves consists of the 4 major layers (bulk rock, muckpile, airgap and cave back). This allows us to efficiently construct a world model with few parameters. This approach also avoids making too many assumptions about the truth and being overly confident in the resulting inversion model, of which all are inherently non-true and non-unique.

3.1.1 Differential model

To simplify the inversion problem, we can take advantage of the fact that gravity is a 'linear' sensor and directly model the difference in structure, rather than having to build a model that captures all local, regional and global contributions to the gravity signal.

The linearity of gravity means that the following two processes produce the same results:

1. model two mass distributions, then subtract

them and calculate the gravitational field of mass difference,

2. model the mass difference directly and calculate its gravitational field.

Under the assumption that the only relevant change in structure is in the block cave itself, process 2 is much simpler. Because the contributions from the rest of the mine and the regional and global mass distributions are the same in both measurements, they cancel out when subtracted and hence need not be modelled at all. This approach holds for the real-world scenario, where the mass changes due to cave evolution vastly dominate the change in gravity signal over time, especially when the gravity sensors are underground and proximal to the cave structures. Nevertheless, it is possible to carry out the inversion process on a larger model volume, including up to the surface at the expense of computation time and further geological constraints.

3.1.2 Ground-truth structure

To obtain ground truth structure, which is the target of the inversion, we subtract the two voxel grids to yield density differences over the time step. These differences are zero almost everywhere except for the volume containing the block cave. To simplify further modelling we define our world model only in this volume.

3.1.3 World model

The world model for this inversion consists of four layers. The parameters of the world model control the height of these layers in the zz direction. Each layer is assumed to have a known, fixed density value illustrated in figure 6. This approach is ideal for scenarios such as block caves, because the target structures within the cave are physically discrete structurally and have disparate densities which we know within a confident range a priori. Thus defining each major structure (bulk rock, muckpile, air gap and cave back) with their estimated densities in a layer-based model is sensible. For the simulation work, we obtained these densities by selecting the statistical modes of the voxel density values in the ground truth models, however in the real inversion case these would be estimated from

knowledge of the bulk material and the properties of the muck pile. The thickness of these layers at any voxel column (xx , yy) are represented by 3 height maps defining the layer boundaries. Any layer's thickness may be zero (except the last layer which is always defined by the distance between the top surface and the top of the volume).

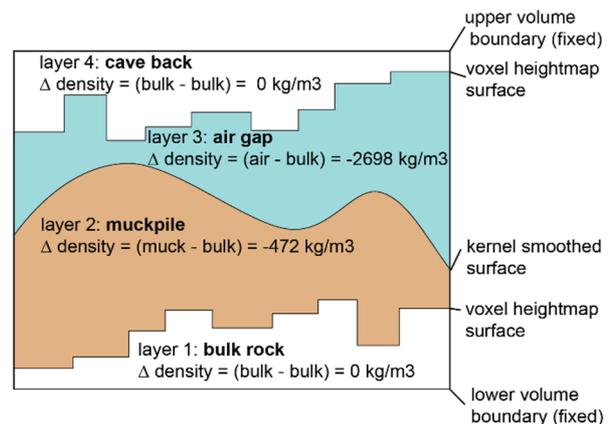


Figure 6 Diagrammatic representation of the world model layer structure, outlining the 4 layers and associated boundaries (not to scale).

As seen in figure 6, we directly parametrise the first layer with voxel heights to account for the known features (including draw bells) and thickness of the hard rock layer between the extraction level and undercut level. This ensures that the inversion model doesn't attempt to provide solutions which require density changes in this hard rock layer. For the second layer which models the top surface of the muck pile, we use a heightmap with a reduced (xx , yy) resolution smoothed with a Gaussian kernel, as we can expect some varying structural character, but generally expect the muck to form in a pile (or piles) in an upwards direction from the cave floor. Finally, the air gap surface is again directly parametrised at voxel resolution to ensure it can express more complex air gap structures. The air gap is one of the highest priority features to correctly characterise due to the safety implications of unknown pockets and air plugs. We want to ensure that any anomalous features that evolve over time are not lost to smoothing or interpolation operations.

To determine the gravity observations arising from a particular set of world model parameters, the world model is voxelised into a regular grid of 10m x 10m x 10m voxels, with shape (32, 34, 24). This shape was chosen for numerical convenience as these voxels are half the extent of the 20 x 20 x 20m voxels in the (16, 17, 12) box that bound the changing region in the original simulation. The additional resolution compared to the ground truth gives the inversion algorithm more flexibility to match the ground truth observations.

3.2 Performance measurement

As this problem is formulated with synthetic ground truth, we have the ability to directly measure the performance of the inversions by comparing them to the true voxel grid. One of the key goals is characterising the structure of the cave back and air gap, so considering differences in height of the cave and the depth of the air layer between the true and inverted solutions provide a useful estimate of performance. We also consider the signed error in the total air volume, an important consideration to understand the model's utility in estimating cave-in risks. Note that, due to the discretised nature of the scenario, the height errors will always be multiples of the voxel height (10m).

To understand how well the proposed inversion solution has fit the observed ground truth, we compare the mean absolute differences of the gravity (difference) measurements. Similarly with other sensors, (see Section 3.3.1) we provide either the absolute error (AE) or the mean absolute error (MAE).

As an additional performance measure, we also consider the total summed mean absolute difference in density evaluated across every voxel between the simulated and true grid. This provides a single number against which to compare different solutions.

3.3 Inversion results

Here we present the results of inversions on the simulated gravity difference data taken in the extraction drives of the true block cave. As a

simple unconstrained gravity inversion has little depth resolution (unless enforced by the world model), we investigate augmenting gravity with other sensors and constraints to improve performance.

3.3.1 Constraints

An inversion model with little or no structural constraints using a priori information, and which is constrained by gravity data alone is unlikely to produce a model with much resolution at depth. This is because any gravity observation can be explained both by placing a small amount of mass near the sensor, or a larger amount further away. To reduce the inherent non-uniqueness of the problem, we consider the following additional data sources and constraints:

1. **Cave wall constraint:** in which the world model is restricted to assigning bulk density to regions outside the known vertical extent of the cave.
2. **Total Extracted mass sensor:** a 'sensor' that measures the total mass extracted from the world model and compares to the ground truth observations.
3. **Drill-hole and cave-floor sensor:** a sensor that directly measures density along two synthetic drillholes placed in the scene and also the known structure of the cave floor (presumably accessible from the extraction drives).

3.3.2 Inverted Cave

The cave inversion result is depicted in Figure 7, with the predicted and ground truth cave heights and air gaps depicted in Figure 8. The height and air gap plots show a good qualitative match between the inversion and the ground truth, with similar topographic structure and air distributed mostly around the edges of the cave.

The difference in the height and air gap indicates that whilst the inversion correctly placed a tall feature in the muckpile in the upper right of the cave, the steepness of the sides of that structure does not exactly match the ground truth, creating the main source of height errors.

The air gap errors are more difficult to interpret.

We suspect that effects from the coarse voxelization of the ground truth are visible here: given that the true air gap is mostly only one or two voxels thick, the higher resolution inversion grid is tending to suggest a smoother solution (as it has double the linear resolution).

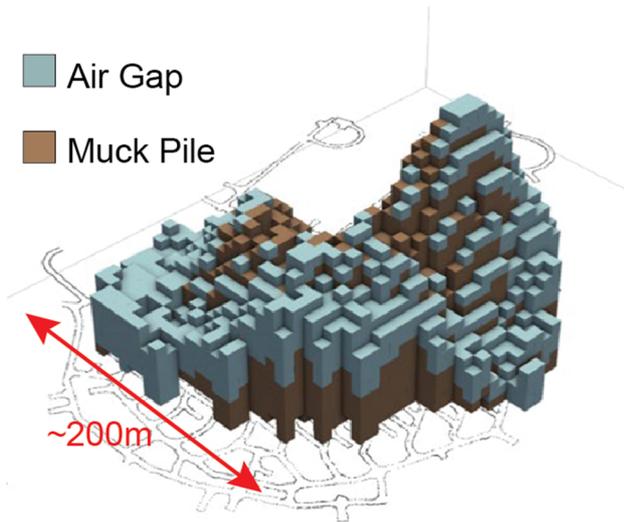


Figure 7 Cave geometry predicted by inversion model 3.

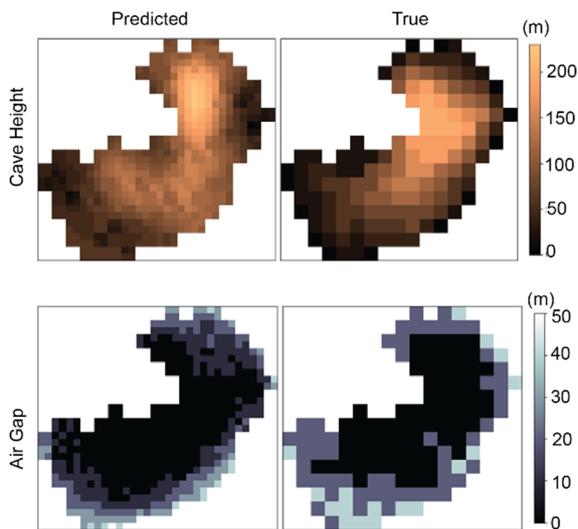


Figure 8 True and predicted cave height and air gap for the constrained inversion solution.

Importantly, the processes and analytics outlined above represent the first, and highly promising steps toward gravity inversions in an underground mining context. There are a number of avenues available to improve and enhance these analytics, outlined in 4.1.

3.3.3 Performance measures

The errors in the reproduction of input observations for these models are given in Table 2. As expected, the gravity-only inversion reproduces the true sensor readings with essentially zero error. This means that the solution, despite being unphysical, is perfectly consistent with the observed gravity. Ruling it out, therefore, must be done either by encoding more geological knowledge into the world model, or adding additional observations.

The gravity-only solution has limited ability in estimating the total mass and also the densities along the drillholes. Again, this would be expected as the inversion algorithm has not been given access to information about these quantities.

Table 2 Sensor measurement reproduction Mean Absolute Errors (MAE) or Absolute Errors (AE) for inversion models with different sensors

Inversion constraints	Gravity MAE (μGal)	Mass AE (Tones)	Drillhole MAE (kg/m^3)
gravity only	0.11	443764	770.82
+cave wall	0.34	383163	234.07
+mass sensor	4.74	226	195.42
+density sensor	6.17	551	57.76

Unsurprisingly, giving the inversion access to an observation dramatically improves its ability to reproduce it. For example, note the large decrease in mass estimation error when the mass sensor is added. However, requiring the inversion algorithm to fit more observations also requires it to compromise on the quality of the fit for each. This is clear, for example, in the gravity fit which gets progressively worse as more sensors/constraints are added. Note, however, that even the worst fit is still, practically- speaking, 'perfect', being at the limit of gravimeter resolution.

Measures of the structural quality of the inversion results are given in Table 3. The

addition of cave wall constraints creates large improvements in the overall density error, the cave height mean absolute error and the total air volume error. The addition of the mass sensor by itself makes small further improvements on the density and height errors but increases the air volume error. Finally, the addition of the density sensor has little impact on the density and height errors but decreases the air volume error significantly.

Table 3 Structural errors for inversion models with different sensors and constraints

Inversion constraints	Density MAE (kg/m ³)	Cave Height MAE (m)	Air Vol. Error (m ³)
gravity only	237.00	63.56	-4,900,000
+cave wall	135.05	40.30	-2,380,000
+mass sensor	132.23	35.76	-3,100,000
+density sensor	133.69	36.32	-2,200,00

As expected, the highest performing solution overall uses the cave wall constraint as well as both mass and density sensors. All solutions under-estimate the air volume, an effect that may be related to our world model parametrisation which biases the model toward adding thickness to lower layers. This is an expected outcome both due to model parametrization/ inversion set-up, and the proximity of the gravity sensors to the lowest layers (extraction drives). The latter reason is actually a benefit to us overall; gravity sensors are most sensitive to mass that is closest to it. While this creates a lack of sensitivity and resolution at depth with surface measurements, our ability to measure at depth close to the resource is a major advancement that is paramount in determining the effectiveness of gravity measurements for resource estimate and monitoring deep underground. Fortunately, choices in building world models and tuning the optimization equations (including depth-weighting) are fully controllable and easily customizable for various scenarios and sites and will be implemented moving forward.

Optimisation tuning and constraints were kept to a minimum in this study. We only used three physical constraints that are confidently estimated by mine operators beforehand, although many other estimates, measurements, and data are available for future studies and real-world surveys. Our conservative approach to prior knowledge with positive results leads us to be optimistic about the validity of the method for upcoming real-world studies.

4 CONCLUSIONS

The ultimate goal of this work is to better characterise the structure of real block caves by conducting timelapse gravity surveys along the extraction drives. To this end, this first-phase simulation study showing the feasibility of the technique on a realistic cave model was performed. Within this program we used density models of the cave at two time-steps provided by mine operators to simulate the gravity signal along the extraction drives. This was used to assess the survey design, optimise the resolution given the expected mass changes from mining, while minimising disruption to operations.

The gravity signal was then used to perform a gravity inversion which was compared to the original density model ‘truth’. The results of this inversion are promising and demonstrate the feasibility of using gravity inversions to recover block cave structures such as muck-pile, airgap, and cave back. The identified structures still exhibit errors that we expect will be improved through using more sophisticated inversion techniques and further geophysical constraints. It is also possible that the current low resolution density models may be contributing to these errors.

The “true” models used to generate the gravity data (and for later quality comparison) are sparse in detail and coarse in resolution. Future real-world data will present much more realistic structure and fluctuation. This will present better opportunity for refining the inversion methods and modelling the fine details of the cave structures. Phase 1 simulations such as those conducted in this study are paramount to choosing the ideal survey parameters, and to identify potential issues before they arise.

The survey parameters identified in this study can be used to initiate a phase 2 study in which the quantum gravimeter is used to measure a real block cave and test the repeatability of the sensor over time for monitoring capabilities.

This work demonstrates the feasibility of gravity inversion modelling of an evolving underground cave using absolute quantum gravity sensors at the extraction level, a novel technology and method not yet seen in the deep mining industry. The prospect of bringing modern gravity surveying which is currently limited to surface and/or static measurements, to deep underground sites is an exciting prospect which will provide new and improved opportunities for cave monitoring and operations.

We see a number of promising avenues forward for improving these analytics and gaining further insight from the data, not least of which is real-world data from future field trials, as well as incorporating geological/ geophysical knowledge of the environment into the inversion process.

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